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A Surveillance Study of Smoke from Heavy-Duty Diesel-Powered Vehicles-Southwestern U.S.A

Southwest Research Inst, San Antonio, Tex

Prepared for

Environmental Protection Agency, Ann Arbor, Mich Div of Motor Vehicle Pollution Control

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A SURVEILLANCE STUDY OF SMOKE FROM HEAVY-DUTY DIESEL-POWERED VEHICLES--SOUTHWESTERN U. S. A.

by
John O. Stormont
Karl J. Springer

INTERIM REPORT

Prepared for
Environmental Protection Agency
Office of Air Programs
Division of Motor Vehicle Pollution Control

September 1972

SOUTHWEST RESEARCH INSTITUTE
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September 1972

Approved:

John M. Clark, Jr.
Technical Vice President
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FOREWORD

This project was conducted for the U. S. Environmental Protection Agency by the Emissions Research Laboratory of Southwest Research Institute, and was an outgrowth of SwRI Proposal No. 11-7234, dated April 20, 1970, entitled "A Surveillance Study of Smoke from Heavy-Duty Diesel-Powered Vehicles--Southwestern U. S. A." The laboratory test phase began in August, 1970, and was completed in June, 1972. The project was subsequently continued for a second year of surveillance activity, so that this interim report covers only the first year's results.

The EPA Project Officer during this period was Mr. Jim Marzen. On August 4, 1972, Mr. John White became Project Officer. The project was under the supervision of John O. Stormont and Karl J. Springer of the Emissions Research Laboratory, and was known within Southwest Research Institute as Project 11-2861.

ABSTRACT

The primary objective of this study was to determine the effectiveness of the Federal diesel smoke regulations in controlling smoke emissions from a group of heavy-duty diesel engines engaged in routine automotive service. A test fleet consisting of 64 trucks and buses, powered by engines certified to meet 1970 smoke standards, was tested for smoke emission at four-month intervals over a one-year period. Changes in smoke opacity observed during this test period were used to determine, to the extent possible, the effect of time, mileage, and type of service (or duty cycle) on opacity. A secondary project objective was to obtain baseline brake specific emissions data of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen for the vehicles in the test fleet.

It was found that, considering the fleet as a whole, smoke opacity tended to increase with time or, equivalently, with mileage. That is, the average opacity of the fleet increased steadily over the baseline opacity at each subsequent inspection. The average smoke opacity for various groups of engines included in the fleet demonstrated the same general trend. At the baseline test, only one engine, representing 1.6 percent of the test fleet, had smoke opacity above one of the 1970 Federal standards. After one year of normal operation, 13 engines, or 20 percent of the fleet, registered opacity over one of these standards. Twelve of these 13 engines exceeded the Federal standard for smoke opacity generated during a full-power lugdown of the engine. Fifty-nine of the 64 fleet vehicles were tested for gaseous emissions and it was found that 43 engines, or 73 percent of those engines tested, met the 1973 California standards for heavy-duty diesel engines. None of these engines met the 1975 California emissions standards.

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I. INTRODUCTION

A. Background

Over the past several years, the Emissions Research Laboratory of Southwest Research Institute has conducted several studies of smoke, odor, and gaseous emissions from diesel-powered trucks and buses. These studies, performed under contracts with the National Air Pollution Control Administration (NAPCA) and the Environmental Protection Agency (EPA), have included a long-range program[1-4] designed especially to characterize these three facets of diesel emissions. In 1967, during Part II of this long-range study, a special investigation[5] was performed to acquire experience with a preliminary smoke test procedure being considered by the Federal Government as a smoke certification test for new diesel engines. This basic procedure, after several revisions, was adopted and made public in several publications[6,7]. Compliance with the Federal smoke standards was required of all heavy-duty diesel engines used in automotive (truck and bus) applications, beginning with engines sold after January 1, 1970. The Federal smoke test, as the test procedure has become known, has undergone slight modification[8], but remains essentially unchanged.

The Federal test was developed solely as an engine dynamometer procedure, and almost no effort was expended in developing a chassis dynamometer version for either compliance purposes or surveillance tests of in-use vehicles powered by certified-model engines. The Emissions Research Laboratory, using a specially designed tandem-axle chassis dynamometer capable of both power absorption and simulation of vehicle inertia, developed a procedure that closely approximates the engine dynamometer test. The development of the chassis procedure was the technical step required for creation of a surveillance study of smoke output from in-use certified model engines. The justification for such a program was an almost total lack of information regarding the smoke characteristics of these certified engines in routine operation in a variety of vehicles and applications.

B. Project Objectives

The principal objective of this project was to determine the continued effectiveness of the Federal exhaust smoke regualtions on heavy-duty diesel engines engaged in routine automotive operation in the southwestern United States. The effect of time, mileage, and type of operation or service on smoke levels of test vehicles was to be determined. A secondary objective was to acquire baseline data on unburned hydrocarbons (HC), carbon monoxide (CO) and nitric oxide (NO), on a brake specific basis, for the test vehicles.

C. Approach

The approach taken to accomplish these objectives was to first develop a test fleet consisting of 64 vehicles powered by the most popular make and

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* Superscript numbers in parentheses refer to the List of References at the end of this report.

model diesel engines. The vehicles were brought to SwRI every four months during a one-year test period to perform the chassis dynamometer version of the Federal smoke test. The data from these tests were analyzed to establish the correlation, if any, between changes in opacity and time, mileage, and type of service. Also, at one of the four smoke inspections, each vehicle underwent a brief 13-mode chassis dynamometer emissions test designed to provide a "map" of HC, CO, and NO output on a brake specific basis.

II. THE TEST FLEET

The test fleet was composed of 64 vehicles powered by a variety of diesel engines. Most of these engines were certified under 1970 Federal smoke regulations. A few uncertified 1969 model engines were included in the fleet, but only when it was established that the 1969 engines were in every respect identical to the corresponding 1970 models.

The engine/vehicle combinations in the test fleet were selected for various reasons. First, the engines were, on the whole, among the most popular makes and models currently used in automotive diesel applications in the U. S. However, some engines were included in the fleet because of their reputation for being heavy smoke producers, even though they were not necessarily the most popular engines. The vehicles in the fleet were selected according to their type of service, such as intercity hauling, intracity delivery, and other categories. This breakdown by duty cycle was necessary since a particular make and model diesel engine may power vehicles engaged in several types of service.

The above selection criteria were, of course, tempered by the availability of new or nearly new vehicles of the types desired. At the time (late summer and fall, 1970) that the fleet was developed, a general economic recession was in progress, and sales volume of new trucks and buses was quite low. Hence, considerable difficulty was encountered in obtaining low-mileage vehicles for the test fleet. This difficulty was overcome by changing the desired fleet composition to include other, more obtainable vehicles, and also by accepting vehicles with higher mileage into the fleet. It was originally planned to include only vehicles with less than 10,000 miles, and this goal was fulfilled for the majority of the fleet vehicles. However, some vehicles could not be obtained in this low-mileage condition, and some concessions were necessary on this point.

The composition of the fleet is given in Table I. The information in Table I is summarized in the following outline.

I. Twenty-one (21) vehicles were powered by two-cycle engines.

   A. Fifteen (15) vehicles were in intracity service.
   B. Six (6) vehicles were in intercity service.

II. Forty-three (43) vehicles were powered by four-cycle engines.

   A. Thirty (30) of these engines were naturally aspirated.
      1. Fifteen (15) vehicles were in intracity service.
      2. Fifteen (15) vehicles were in intercity service.

TABLE 1. VEHICLES IN TEST FLEET

Quantity	Engine/Vehicle Description	Type of Service
10	Detroit 6V-71N/GM Bus	Intracity
5	Detroit 8V-71N/Truck-Tractor	Intercity
1	Detroit 8V-71N/ Bus	Intercity
10	Cummins NH-250/Truck-Tractor	Intercity
5	Cummins V-903/Truck-Tractor	Intercity
4	Cummins NTC-335/Truck-Tractor	Intercity
5	Mack ENDT 675/Garbage Truck	Intracity
2	Mack ENDT 675/Truck-Tractor	Intercity
2	Mack ENDT 673 B/Truck-Tractor	Intracity
5	Caterpillar 1145/Truck	Intracity
5	Caterpillar 1150/Truck-Tractor	Intracity
4	GM DH-478/Truck-Tractor	Intracity
5	Detroit 6V-53N/Van	Intracity
1	IHC DV 550B/Dump Truck	Intracity
64	Total	

B. Thirteen (13) of these engines were turbocharged.
   1. Seven (7) vehicles were in intracity service.
   2. Six (6) vehicles were in intercity service.

It can be seen that the fleet was well-balanced with regard to two-cycle and four cycle engines, naturally aspirated and turbocharged four-cycle engines, and intracity and intercity vehicles. Some of the test vehicles are shown in Figures 1, 2, and 3. More specific information concerning the engines in the test fleet is given in Table 2.

Municipal Bus Powered by
General Motors 6V-71N Engine

Intercity Bus Powered by
Detroit Diesel 8V-71N Engine

Intercity Truck-Tractor Powered by
Detroit Diesel 8V-71N Engine

Intercity Truck-Tractor Powered by
Cummins NH-250 Engine

FIGURE 1. TYPICAL VEHICLES FROM SURVEILLANCE TEST FLEET

Intercity Truck-Tractor Powered by Cummins V-903 Engine

Intercity Truck-Tractor Powered by Cummins NTC-335 Engine

Intercity Truck-Tractor Powered by Mack ENDT 675 Engine

Intracity Truck-Tractor Powered by Mack ENDT 6735 Engine

FIGURE 2. TYPICAL VEHICLES FROM SURVEILLANCE TEST FLEET

Intracity Delivery Truck Powered by Caterpillar 1145 Engine

Intracity Truck-Tractor Powered by Caterpillar 1150 Engine

Intracity Truck-Tractor Powered by GM DH-478 Engine

Intracity Delivery Van Powered by Detroit Diesel 6V-53N Engine

FIGURE 3. TYPICAL VEHICLES FROM SURVEILLANCE TEST FLEET

TABLE 2. BASIC ENGINE CONFIGURATIONS IN SURVEILLANCE FLEET

Make and Model	Strokes/ Cycle	Cylinder Arrangement	Displacement, cu in	Aspiration	Horsepower @ Rated rpm	Torque, lb-ft at rpm
Detroit Diesel 6V-71N	2	6-V	426	Natural	210 @ 2100	604 @ 1200
Detroit Diesel 6V-71N	2	6-V	568	Natural	310 @ 2100*	800 @ 1600
Cummins NH-250	4	6-I	855	Natural	250 @ 2100	658 @ 1500
Cummins V-903	4	8-V	903	Natural	240 @ 2400**	707 @ 1800
Cummins NTC-335	4	6-I	855	Turbochgd	335 @ 2100***	927 @ 1500
Mack ENDT 675	4	6-I	672	Turbochgd	235 @ 2100	890 @ 1200
Mack ENDT 673B	4	6-I	672	Turbochgd	250 @ 2100	700 @ 1600
Caterpillar 1145	4	8-V	522	Natural	175 @ 3200	353 @ 1700
Caterpillar 1150	4	8-V	573	Natural	200 @ 3000	446 @ 1400
GM DH-478	4	6-V	478	Natural	165 @ 2800	325 @ 2000
Detroit Diesel 6V-53N	2	6-V	318	Natural	195 @ 3600	421 @ 1400
IHC DV 550B	4	8-V	549	Natural	200 @ 3600	– @ 2000

*290 hp with LSN 55 injectors also tested
**320 hp @ 2650 rpm also tested
***280 hp version also tested

III. TEST PROCEDURES, INSTRUMENTATION, AND FUELS

The vehicles in the test fleet underwent tests to measure smoke opacity and gaseous emissions of unburned hydrocarbons (HC), carbon monoxide (CO), and nitric oxide (NO). This section of the report describes the test procedures of this surveillance study, as well as the test instrumentation and fuels used.

A. Smoke Test Procedure and Instrumentation

In 1968, the Federal government established standards for smoke output from 1970 and later model diesel engines used in vehicles above 6,000 pounds GVW. Compliance with these standards was (and is) determined by subjecting a typical production engine, representative of a certain class or family of engines, to the Federal smoke compliance test, an engine dynamometer procedure (Appendix A). However, the developmental work for this procedure involved the operation of several diesel-powered truck-tractors on a special chassis dynamometer at SwRI. This work, though revised several times, formed the basis of the Federal smoke compliance test.

The Emissions Research Laboratory successfully developed a chassis-dynamometer version of the Federal smoke test, and it is known that the two procedures correlate well. The key item in the chassis procedure is a specially-equipped Clayton tandem-axis dynamometer with a power absorption capability of 200 horsepower per axle. Large flywheels attached to one end of the dynamometer rolls provide up to 41,000 pounds of vehicle inertia simulation. Figure 4 shows a bus under test on this dynamometer.

The Federal smoke compliance test, as performed on engine or chassis dynamometer, consists of an initial engine acceleration from 150-250 rpm above idle speed to 85-90% of rated engine speed in 5.0 ± 1.5 seconds, a second acceleration from peak torque speed (or 60% of rated speed, whichever is higher) to 95-100% of rated speed in 10.0 ± 2.0 seconds, and (following this second acceleration) a full-power lugdown from 95-100% of rated speed to the particular intermediate engine speed (peak torque speed or 60% of rated speed) in 15.0 ± 5 seconds. The accelerations are made against simulated vehicle inertia furnished by large flywheels connected to the dynamometer rolls or shaft, and/or against a preset load in the power absorption unit. A schematic drawing of engine speed vs time is illustrated in Figure 5. Three of these sequences constitute one smoke test.

The average smoke opacity from the 15 highest-valued one-half second intervals of the two accelerations determine the "a" Factor, and the average opacity from the five highest-valued one-half second intervals determines the "b" Factor. The maximum values currently allowed for "a" and "b" Factors of certification engines are 40- and 20-percent opacity, respectively. There is a strong possibility that these maximum values will be lowered to 20- and 15-percent opacity, respectively, for 1974 and beyond.

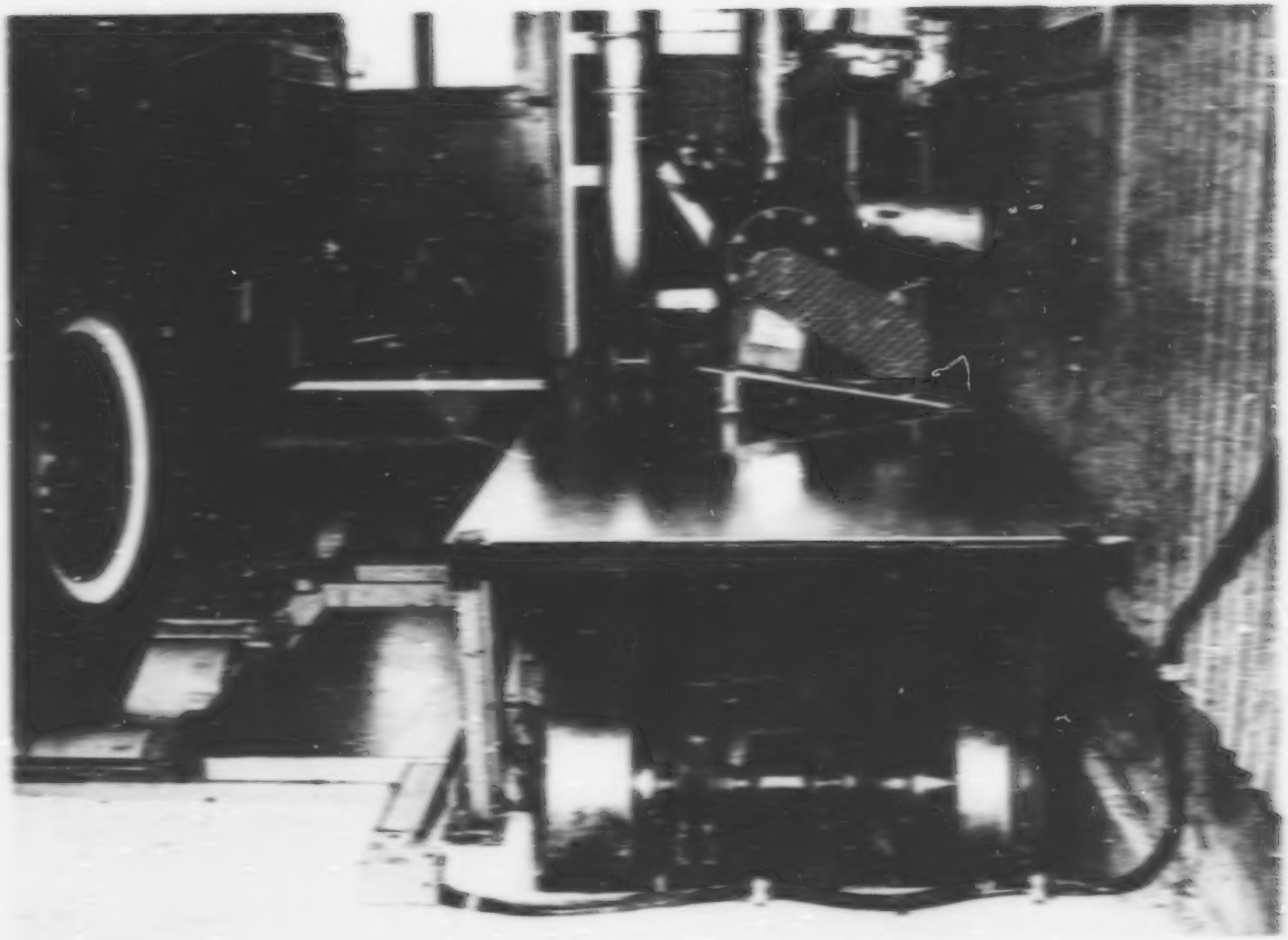


FIGURE 4. CITY BUS UNDER TEST ON 5-HP DYNAMOMETER (INERTIA SIMULATION WHEELS IN RIGHT FOREGROUND)

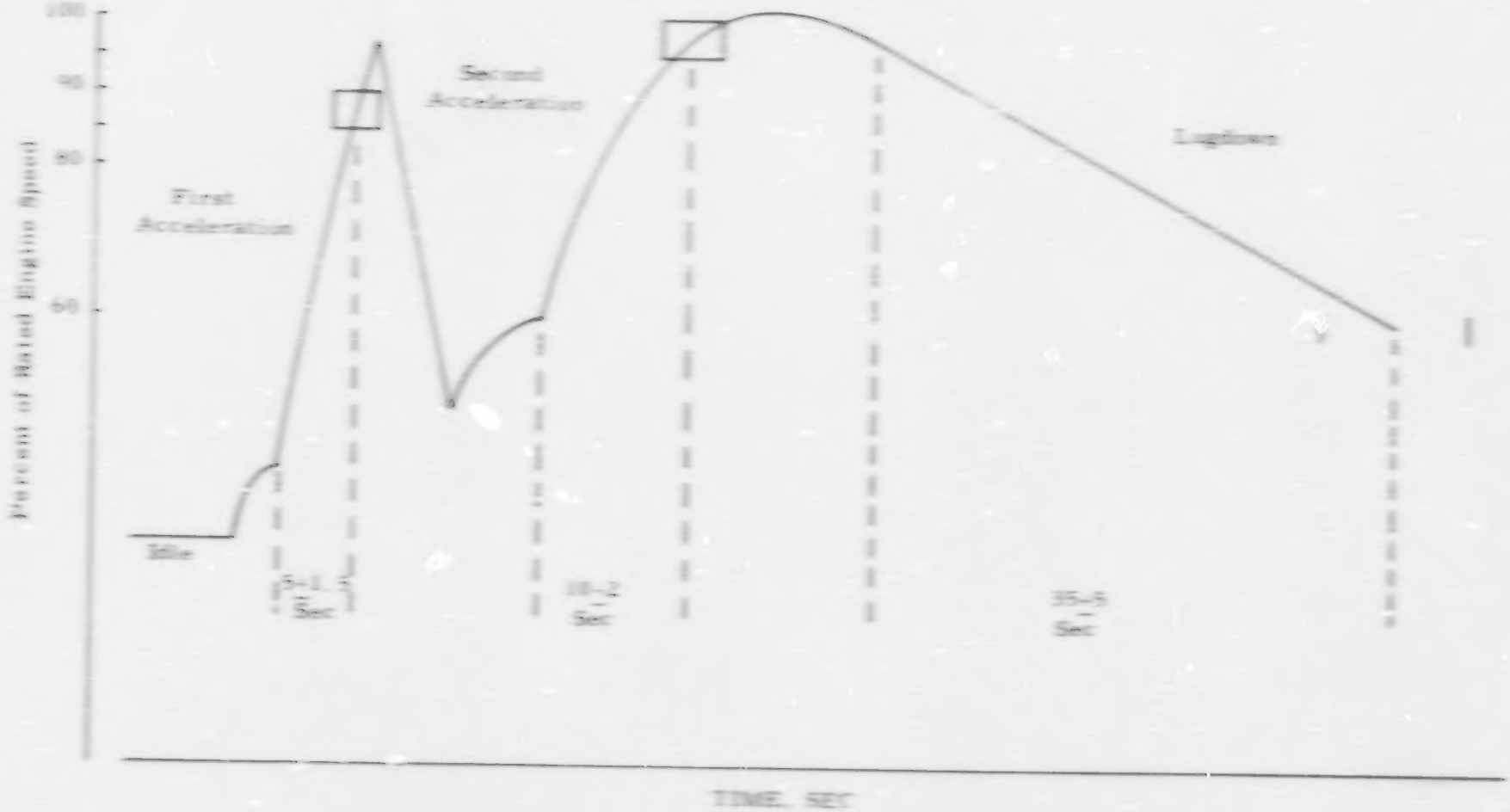


FIGURE 5. SCHEMATIC OF FEDERAL SMOKE COMPLIANCE TEST - ENGINE SPEED VS TIME

It is also likely that 1974 standards will include a "c" Factor, which is the average of the opacities from the three highest-valued one-half second intervals in the test. The maximum allowable "c" Factor value will probably be 50-percent opacity. The exact nature of the 1974 Federal smoke standards had not been made public at the time this report was written.

All vehicles were tested in their "as received" condition, with no adjustments made to the engine. However, a brief pre-test inspection, consisting of a search for anomalies such as crimped or leaking fuel lines, was conducted. Following each smoke test, a power curve (i.e., a series of full-power conditions at various engine speeds) was performed. During this power curve, measurements of rear-wheel horsepower, smoke opacity, and (where possible) inlet restriction, exhaust backpressure, injection system pressure, and turbocharger boost pressure were recorded. These performance parameters were recorded for reference in case the smoke level of any vehicle changed substantially from one test to the next. Thus, it was possible to diagnose the more obvious causes of increased smoke opacity.

The U.S. Public Health Service full-flow, light-extinction smokemeter (Figure 6) was used to measure exhaust smoke opacity for all tests. The PHS instrument is specified for use in the smoke certification test procedure and is the standard diesel smokemeter used by government and industry.

In the surveillance-type tests conducted for this project, it was not possible to mount the smokemeter directly onto the vehicle exhaust pipe outlet. Hence, a standard method of mounting the smokemeter was developed. First, a piece of steel exhaust pipe approximately three ft long was welded to a piece of flexible exhaust pipe about three or four ft long. The other end of the flex pipe was connected to the vehicle's exhaust outlet, and the smokemeter mounted on the end of the steel exhaust pipe. The diameter of the pipe on which the smokemeter was mounted was determined by the horsepower rating of the engine, per the Federal smoke test procedure. Also, the smokemeter was located on the exhaust pipe so that the distance from the light beam to the end of the pipe was 1.0 to 1.5 pipe diameters, again per the Federal procedure.

Two smokemeters were used on vehicles equipped with dual exhaust outlets. For instance, the intercity tractors powered by 8V-71 engines had dual 3.5-inch diameter exhaust stacks. Each stack had its own muffler and served only one bank of the engine. Since the two exhaust systems were separate and independent of each other, it was decided to treat the engine as two separate engines, each with its own exhaust system. The 8V-71 engine is rated 318 horsepower; therefore, each side of its exhaust system was considered to serve a 159-horsepower engine. Thus, two smokemeters were used, each mounted on a three-inch diameter pipe adapted to the 3.5-inch exhaust stack.

FIGURE 4. PMS FULL-FLOW, LIGHT-EXTINCTION SMOKEMETER

Smokemeter output and engine speed were recorded on a Texas Instruments dual-pen strip chart recorder with 10-mv range and 0.4 second full-scale response. Recorder chart speed was 12 in per min, which allowed accurate analysis of the opacity traces. Typical smoke opacity and engine speed traces for naturally aspirated and turbocharged diesel engines are shown in Figures 7 and 8, respectively.

B. Gaseous Emissions Test Procedure and Instrumentation

The California Air Resources Board (ARB) 13-mode, 39-min chassis dynamometer test procedure (Appendix B) was used to obtain gaseous emissions data for the test vehicles. Each vehicle tested for emissions performed two tests in a back-to-back manner. A special 30-min version of the test cycle was used for city buses in order to lessen tire heating problems. Mode times were reduced to two min except for modes 3, 7, 8, and 12, which remained three min long. No difficulty was encountered in stabilizing engine speed and load conditions in the time-shortened modes.

Measurement of unburned hydrocarbons (HC), carbon monoxide (CO), and nitric oxide (NO) were made according to SAE Recommended Practices J215 (HC) and J177 (CO and NO). These Practices are part of the ARB test procedure. The NDIR analyzers for CO and NO are shown in Figure 9, and the high-temperature FIA unit for HC is shown in Figure 10. Note the very short heated sample line for the FIA in this latter figure. Engine fuel consumption was measured by means of a mass flowmeter-float tank arrangement manufactured by Flo-Tron, Inc. Temperature of fuel supplied to the engine was maintained in the specified range of 100° F ± 10° F by a heat exchanger in the fuel flow measurement system. Engine air consumption (or exhaust flow) was taken from data furnished by the engine manufacturer for a particular engine model.

C. Test Fuels

All smoke and emissions tests were run on No. 1 or No. 2 diesel fuel which met the specifications given in the Federal Register, Vol. 33, No. 108, Part II, p. 8320, para. 85.12[1](b), dated June 4, 1968. The laboratory analysis of typical batches of No. 1 and No. 2 fuel are given in Table 3.

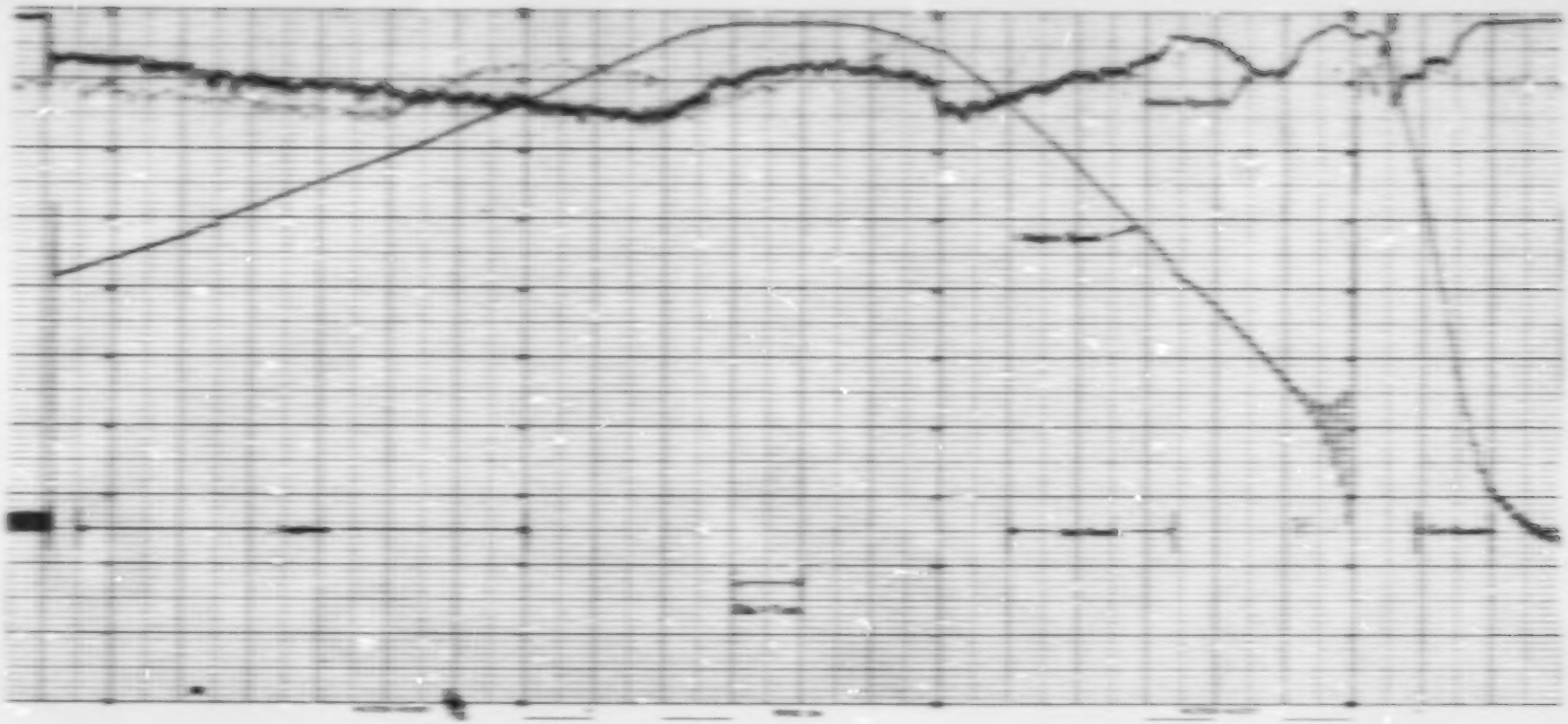


FIGURE 1. SMOKE OPACITY AND ENGINE SPEED TRACES FROM FEDERAL TEST OF NATURALLY ASPIRATED ENGINE

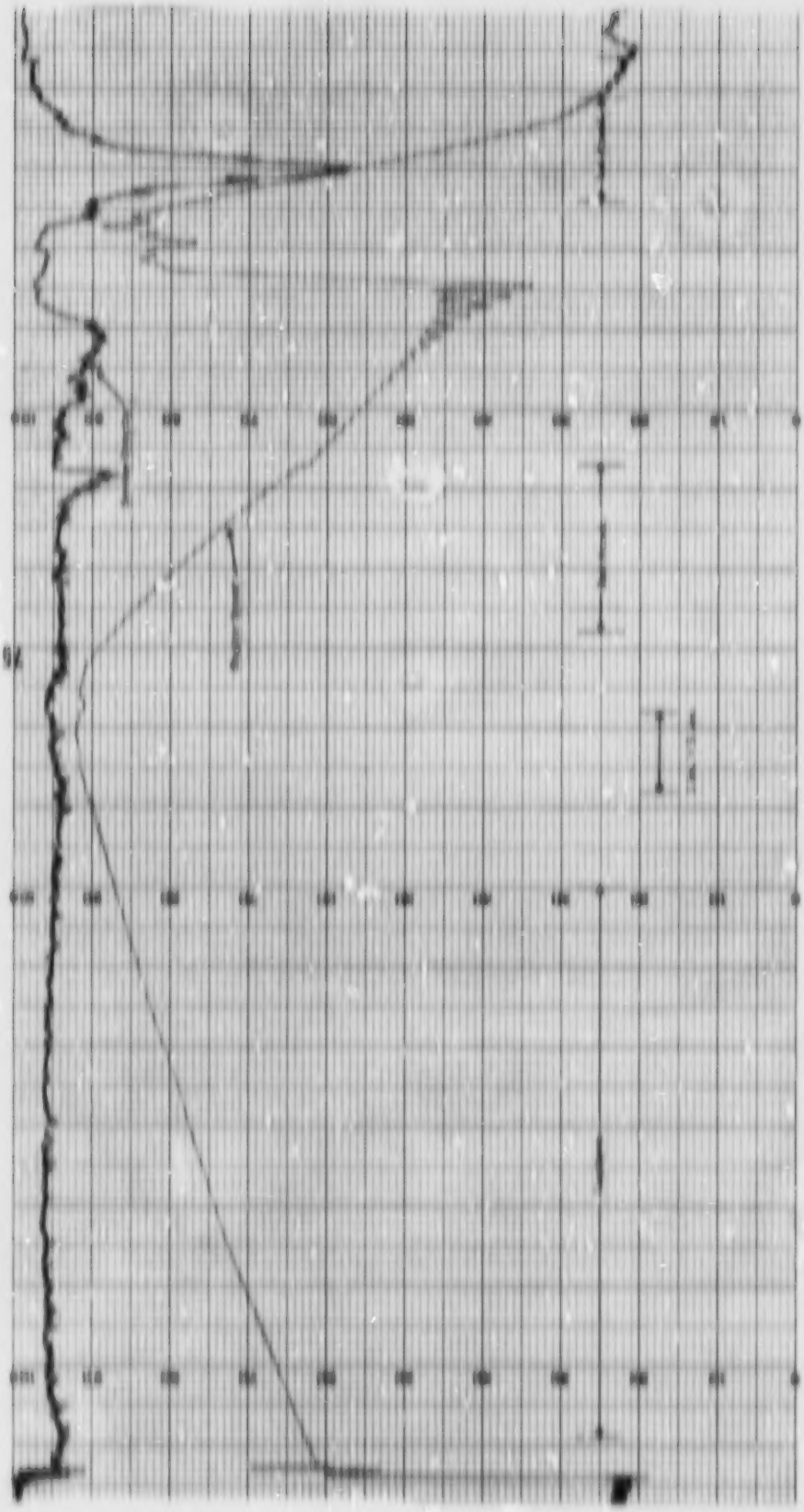


FIGURE 4. SMOKE OPACITY AND ENGINE SPEED TRACES FROM FEDERAL TEST OF TURBOCHARGED ENGINE

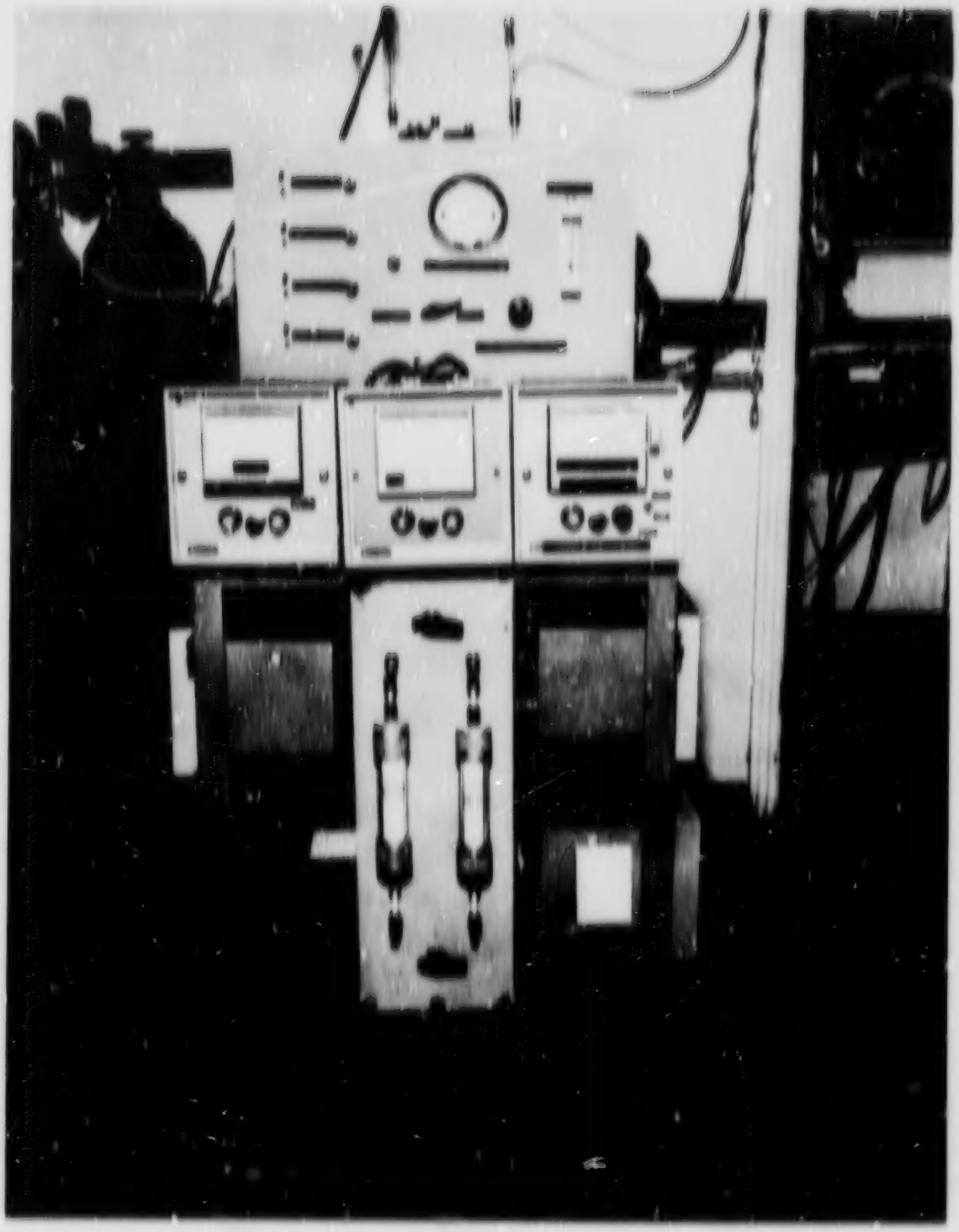


FIGURE 9. INSTRUMENT CART FOR SAMPLING DIESEL EMISSIONS BY NDIR ANALYZERS

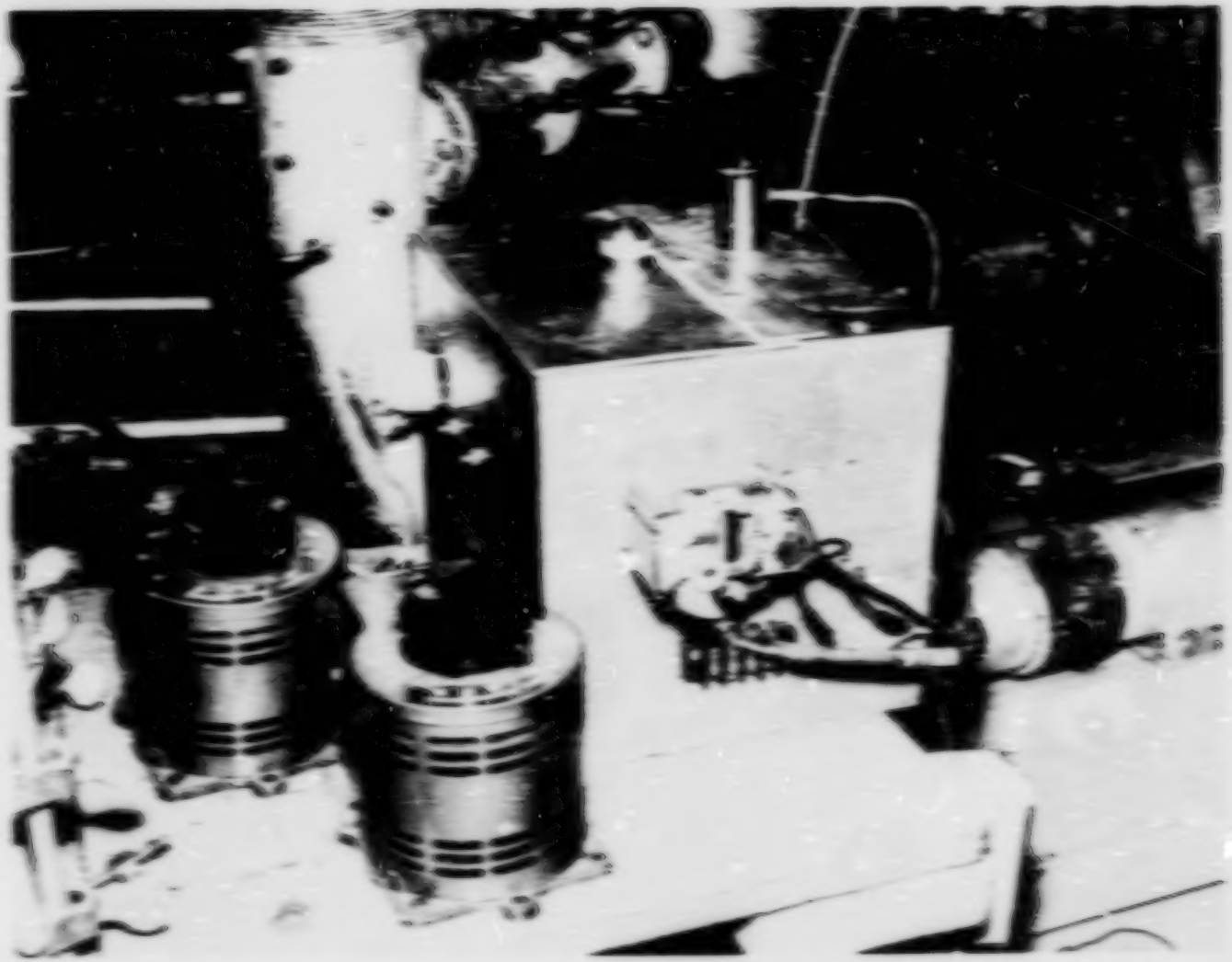


FIGURE 10. SwRI HIGH-TEMPERATURE ANALYZER FOR UNBURNED HYDROCARBONS

TABLE 1. TYPICAL TEST FUELS SPECIFICATIONS

Fuel Type	No. 1	No. 2
Fleet Application	City Buses	All Others
Property		
Cetane	48.0	44.0
Pour Point, °F	-40	+10
Flash Point, °F	164	182
Gravity, °API	42.0	33.8
Viscosity, cent.	1.7	2.6
Hydrocarbon Composition: Aromatics, %	14.0	36.7
Total Sulfur, wt. %	0.06	0.30
Distillation, °F:		
IBP	389	376
10%	406	442
50%	426	522
90%	486	583
EP	547	640

IV. SUMMARY OF FIRST YEAR'S SMOKE TEST RESULTS

This section contains all the results from the first year (Test Rounds 1-4) of project testing. The test data appear in tabular form and also in bar charts for each engine/vehicle group. These groups are as follows: two-cycle engines in intracity service; two-cycle engines in intercity service; four-cycle naturally aspirated engines in intercity service; four-cycle turbocharged engines in intracity service; four-cycle turbocharged engines in intercity service; and midrange two-cycle and four-cycle engines in intracity service. Some general comments accompany the test results for each of these groups, but the reader is, of necessity, relied on to obtain more specific information from the various tables and bar charts. A simple statistical analysis of the data appears in each table, for each engine group. A more extensive analysis is postponed to the next section.

A word concerning some of the terminology used in this and subsequent sections dealing with smoke test results: The term "baseline" refers to the initial or 0-month test of a vehicle. Subsequent tests at 4, 8, and 12 months of operation are referred to as "second round" (or merely "second test"), "third round", and so forth. The term "last test" or "last inspection" always refers to the fourth-round or 12-month test. Results of these smoke tests, the Federal "a" and "b" Factors, are often referred to collectively as "smoke factors".

A. Two-Cycle Engines in Intracity Service

The data from the four tests of these municipal buses are given in Table 4 are illustrated in Figure 11 ("a" Factors) and Figure 12 ("b" Factors). The average smoke factors for the four tests are illustrated by the first group of bars in Figure 15.

These engines were characterized by low smoke opacity throu[illegible] the one-year test period. The highest "a" and "b" Factors at the initial test were approximately 10- and 8.5-percent opacity, respectively. The initial mileages for these vehicles ranged from 25,400 to 39,200 miles. Only slight changes from the baseline "a" and "b" Factors were observed at the second- and third-round tests. Note that the average smoke factors at these tests differed little, if any, from those of the initial test.

There also was little change between the initial and last (12-month) sets of data, with one exception, which will be noted presently. The highest fourth-round "a" and "b" Factors were about 9- and 7-percent opacity, respectively. Five engines had increased "a" and "b" Factors over baseline, and five engines showed decreased smoke factors. The average fourth-round "a" and "b" Factors were very close to those of the first test. Elapsed test mileage after one year of operation ranged from 60,200 to 68,000 miles, while total vehicle mileage was 90,000 to 100,000 miles. This latter figure is defined as the useful life of a heavy-duty diesel engine

TABLE 4. TWO-CYCLE ENGINES IN INTRACITY SERVICE

Engine: Detroit Diesel 6V-71N (L28 HP Supercharged)
Vehicle: GM Bus

No.	Actual Mileage	First-Hour Test PMS Smoke Opacity, % "A" Factor	First-Hour Test PMS Smoke Opacity, % "B" Factor	Elapsed Test Miles	Second-Hour Test PMS Smoke Opacity, % "A" Factor	Second-Hour Test PMS Smoke Opacity, % "B" Factor	Second-Hour Test Differences*, % "A"	Second-Hour Test Differences*, % "B"
615	34,259	5.8	4.7	22,346	7.2	7.6	+1.4	+2.9
616	22,467	6.4	6.2	72,133	7.8	8.1	+1.4	+1.9
617	15,575	12.2	7.4	28,473	9.6	5.6	-2.6	-1.2
618	31,700	6.1	6.4	22,858	6.4	7.1	+0.3	+0.7
619	36,277	6.9	8.1	26,291	7.6	7.5	+1.2	-7.6
620	32,485	4.6	7.7	22,890	3.5	3.3	-1.1	-0.4
621	31,982	6.0	4.6	26,155	6.7	6.4	+0.7	+1.8
622	32,340	6.8	7.9	27,348	5.1	5.3	-1.7	-1.7
623	33,781	4.3	3.4	25,978	4.3	4.4	+0.2	+1.0
624	31,479	4.2	3.7	25,784	3.8	2.6	+2.2	-1.1
Average		6.4	5.8	Average	6.1	6.1		
Mean Deviation		1.7	1.9	Mean Deviation	1.7	1.8		
Standard Deviation		1.8	1.8	Standard Deviation	2.0	1.7		
Coefficient of Variation		0.28	0.32	Coefficient of Variation	0.33	0.28		

No.	Elapsed Test Miles	Third-Hour Test PMS Smoke Opacity, % "A" Factor	Third-Hour Test PMS Smoke Opacity, % "B" Factor	Third-Hour Test Differences*, % "A"	Third-Hour Test Differences*, % "B"	Elapsed Test Miles	Fourth-Hour Test PMS Smoke Opacity, % "A" Factor	Fourth-Hour Test PMS Smoke Opacity, % "B" Factor	Fourth-Hour Test Differences*, % "A"	Fourth-Hour Test Differences*, % "B"
615	46,794	6.2	4.9	+0.4	+0.2	50,340	5.4	4.9	-0.4	-0.7
616	45,232	9.5	4.6	-0.9	-1.6	68,870	8.9	7.1	+2.5	+0.9
617	45,697	9.4	7.3	-0.8	-0.1	46,273	1.97	2.39	-0.4	-5.3
618	46,760	7.9	7.2	+1.8	+0.8	68,673	6.8	6.3	+0.7	-0.3
619	47,247	8.3	7.9	-2.3	-0.6	65,796	7.9	6.9	-0.7	-1.9
620	46,777	2.7	4.8	+1.3	+1.3	65,338	5.7	6.8	+1.3	+0.3
621	46,386	2.7	7.8	+2.7	+2.2	66,496	8.3	5.7	+2.3	+0.9
622	46,974	4.8	3.4	-2.8	-2.3	62,467	6.7	6.3	-0.1	-1.4
623	46,569	6.4	6.7	+1.9	+1.3	70,854	7.3	5.2	+2.9	+1.8
624	46,829	4.1	2.2	-1.7	-1.5	66,294	4.0	4.1	-0.4	+0.4
Average		6.4	5.6	Average	6.1	5.4		
Mean Deviation		2.7	1.9	Mean Deviation	2.1	0.9		
Standard Deviation		3.3	1.8	Standard Deviation	1.6	1.1		
Coefficient of Variation		0.36	0.32	Coefficient of Variation	0.28	0.20		

*Zero = Smoke-o-scope limit.
**Data not included in statistical analysis.

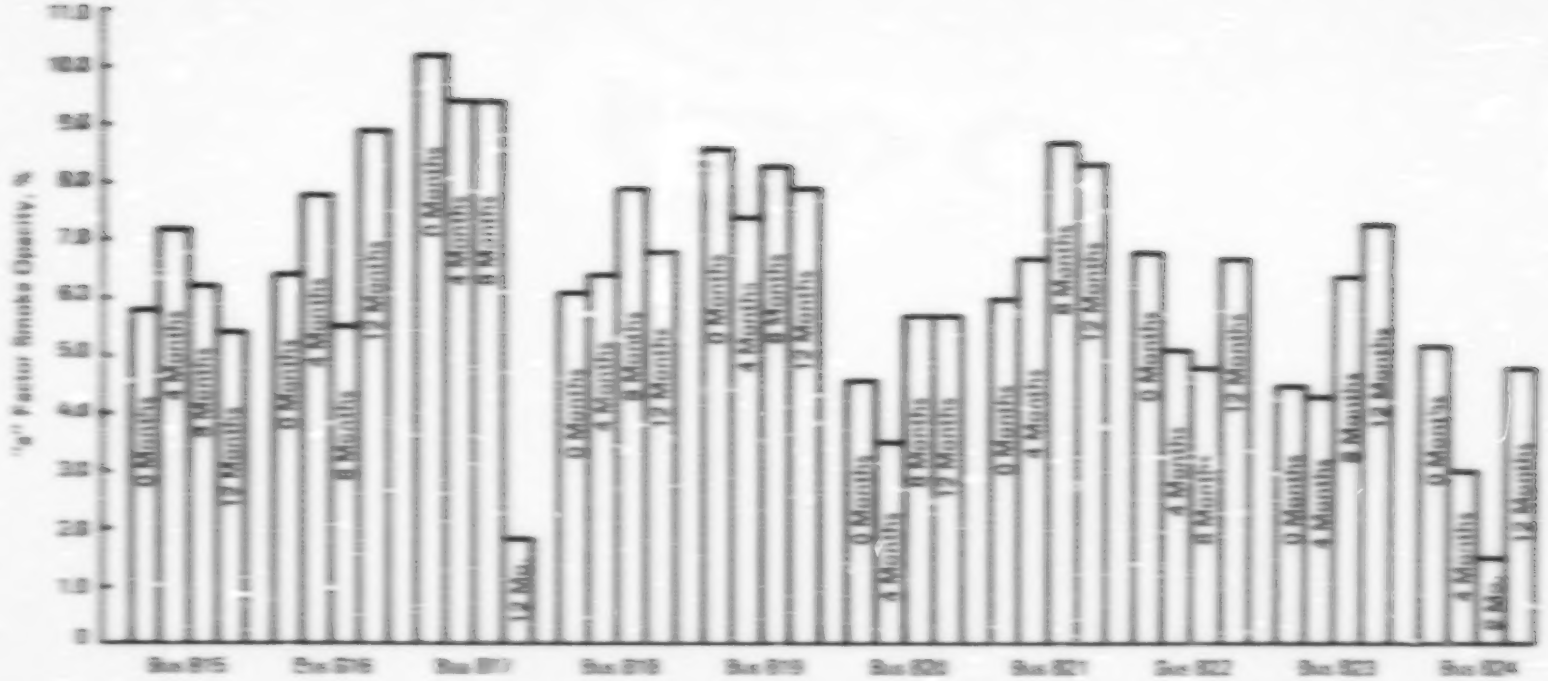


FIGURE 11. FEDERAL "a" FACTORS FOR TEN DETROIT DIESEL 6V-71N ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

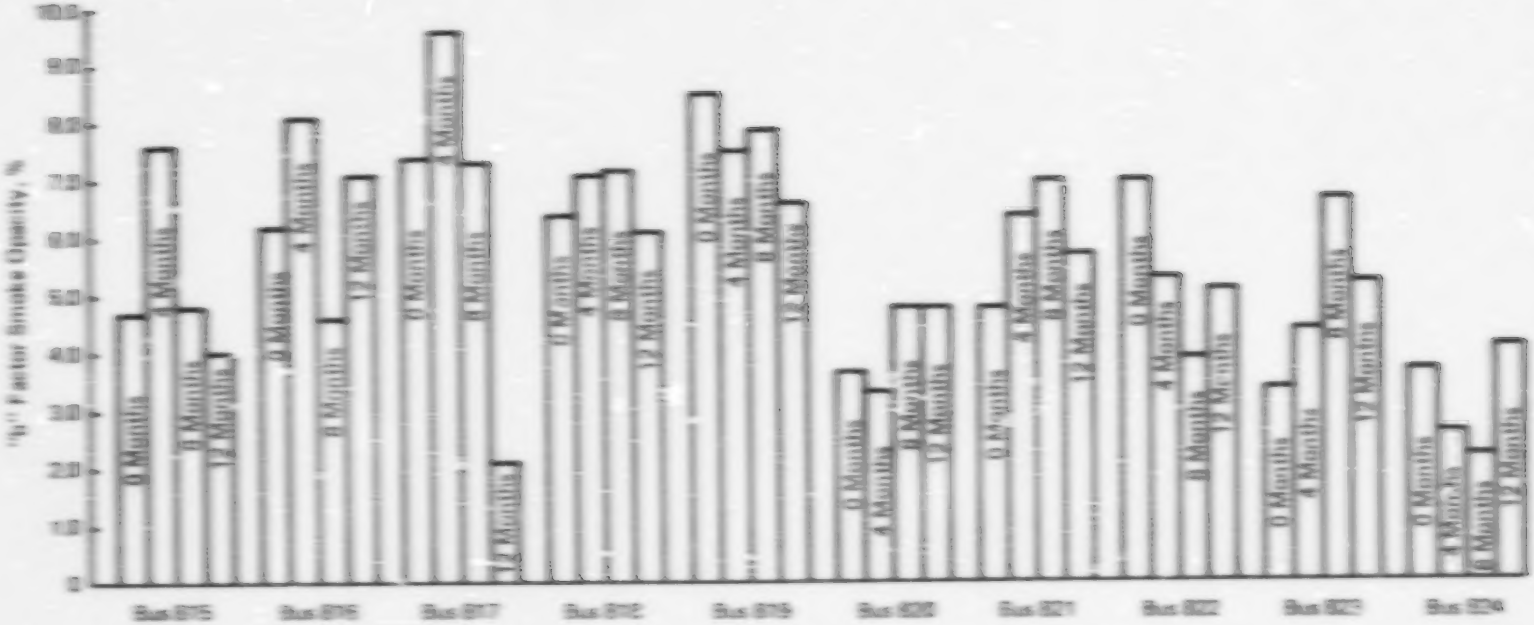


FIGURE 12. FEDERAL "b" FACTORS FOR TEN DETROIT DIESEL 6V-71N ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

(Federal Register, Vol. 36, No. 166, dated August 26, 1971).

The only engine in this group that had a large and abrupt change in smoke opacity during the test period was in Bus No. 817. Shortly after the third-round test, this engine received a major overhaul consisting of new rings, cylinder liners, camshafts, injectors, and a valve job. The bus was returned to the Emissions Research Laboratory after a short break-in period, and another smoke test and power curve were performed. The "a" and "b" Factors were approximately 1.5- and 1.0-percent opacity, respectively. Rear wheel power was about the same as when the bus was first tested at 35,500 miles. Engine failure was quite sudden, and for this reason the third-round tests results were thought to represent the smoke prior to any substantial engine deterioration. Hence, these data are included with the other third-round results. Incidentally, this was the only engine in this group to undergo extensive maintenance; the others had only routine service performed on them.

The data from the four inspections have been statistically analyzed to obtain not only mean values, but also the quantities associated with the dispersion or variation of the data about these mean values, namely, the mean deviation, standard deviation, and the coefficient of variation. The standard deviation gives the absolute variation of the data, while the coefficient of variation expresses the standard deviation as a percentage of the mean and hence is a relative measure of variation. For example, the mean (average) values of the first-round "a" and "b" Factors are similar (6.4- and 5.6-percent opacity, respectively) and their standard deviations are the same (1.8). However, the "b" Factors have a larger coefficient of variation and therefore have a higher degree of relative dispersion.

It should be noted that the fourth-round smoke factors for Bus No. 817 were not included in the statistical analysis. This omission was thought justified since the recently overhauled engine had very low smoke factors that artificially lowered the mean values and increased the variability of the data. Also, the failure of a heavy-duty diesel engine after only 80,000 miles of operation is certainly an uncommon event. Hence, it was thought that the surveillance nature of the project would best be served if the test results for this vehicle were reported, but no statistical significance attached to them.

In general, the variation of the data was consistent and rather large through the first three inspections, then dropped sharply at the last test. Therefore, at least for this last inspection, the data showed a greater tendency to converge to a central value. It is, of course, not possible to conclude if this trend would continue in the future. The "a" Factors generally showed the largest absolute variation at each of the four tests, while the "b" Factors had the greatest relative variation.

B. Two-Cycle Engines in Intercity Service

The "a" and "b" Factors for these engines are presented in Table 5 and shown in Figures 13 and 14, respectively. The average "a" and "b" values are illustrated by the second and third set of bars in Figure 15. Five engines powered truck-tractors in line-haul service, and one engine was in an intercity bus. The truck-tractors were equipped with dual exhaust stacks, and, as previously mentioned, smoke opacity was measured separately and simultaneously for each stack. The smoke factors generated by the left and right engine banks are hence presented separately in Table 5 and in the accompanying figures. It can be seen from these data that the two banks of an engine often produced smoke of very different opacity.

These engines, like the 6V-71 bus engines, had low smoke factors at all four of the tests. The first-round "a" Factors ranged from 1.5- to 7.3-percent opacity, while the corresponding "b" Factors ranged from 1.0- to 5.4-percent opacity. Vehicle mileages at this initial test were low, from about 5,200 to 12,900 miles. At the second inspection, there were an equal number of engines with increased and decreased smoke opacity from the baseline values. Note that the average "a" and "b" Factors were nearly identical at the first- and second-round tests. By the third inspection, all but one engine had higher smoke opacity than at the initial test, and the average "a" and "b" Factors were approximately twice the values of the baseline averages.

The fourth-round smoke factors were still low, especially in view of the very high mileage accumulated by these vehicles. The "a" Factors ranged from 4.8- to 14.1-percent opacity, and their average was 9.5-percent opacity. The "b" Factors went from 2.0- to 10.9-percent opacity, with an average of 4.6-percent opacity. Elapsed test mileage for the one-year period was 114,000 to 170,000 miles, and total vehicle mileage at the last test was 127,000 to 176,000 miles. None of the engines underwent any maintenance that could have greatly affected the smoke opacity (e.g., maintenance of the injection system or internal parts of the engine).

The data from the four inspections of these vehicles were statistically analysed in the same manner as the data for the city buses. However, for statistical purposes, the test results for the left and right engine banks of the five truck-tractors were considered as discrete and independent results (which indeed they are). In other words, the statistical analysis considers the results as arising from tests of ten four-cylinder, single exhaust engines. This approach is justified by the fact that no satisfactory method of combining smoke opacities from two sources (stacks) exists, as it does for the brake specific mass-flow emissions data of the emissions tests.

The variation of the data was rather large, as can be seen from the standard deviations and coefficients of variation in Table 5. The "a"

TABLE 5. TWO-CYCLE ENGINES IN INTERCITY SERVICE

No.	Initial Mileage	First-Axle Test (165 Meter Opacity, %) "a" Factor	"b" Factor	Elapsed Test Miles	Second-Axle Test (165 Meter Opacity, %) "a" Factor	"b" Factor	Difference, 4"K'	Difference, 4"K'	Elapsed Test Miles	Third-Axle Test (165 Meter Opacity, %) "a" Factor	"b" Factor	Difference, 4"K'	Difference, 4"K'	Elapsed Test Miles	Fourth-Axle Test (165 Meter Opacity, %) "a" Factor	"b" Factor	Difference, 4"K'	Difference, 4"K'
Engine: Detroit Diesel 4R—71N (L33 HI Supercharged Vehicle: Coach—Gasoline																		
									Left Engine Data									
401	5,480	2.4	1.3	10,100	1.7	1.0	-0.7	-0.1	86,000	5.3	1.2	-0.4	+0.4	124,000	1.0	1.1	+0.4	+0.8
334	1,140	7.4	4.7	56,100	10.1	4.9	+2.7	+0.2	109,700	17.6	9.3	+10.4	-4.6	170,400	14.1	10.4	+6.7	+6.2
335	5,300	1.5	1.1	56,300	3.9	1.7	+2.4	+0.4	90,500	6.7	2.7	+7.2	+1.4	139,200	4.7	3.0	+6.2	+1.7
336	4,100	4.9	1.2	40,500	2.7	1.2	-1.9	+2.8	65,300	8.4	4.3	+1.8	-0.9	102,900	8.4	3.4	+3.8	+0.2
337	12,200	6.9	5.4	46,600	5.2	3.1	-1.7	-2.3	77,300	5.7	1.4	-3.2	-3.8	124,600	12.7	6.9	+5.8	-0.5
									Right Engine Data									
401	5,480	2.1	1.8	10,100	4.7	1.1	+0.6	-0.5	86,700	7.9	5.3	+5.4	+3.7	124,000	4.8	3.2	+2.5	+0.8
334	1,140	4.1	1.8	56,100	4.8	1.2	+0.7	+0.4	109,700	8.3	2.4	+4.8	+0.8	170,400	7.1	2.4	+3.5	+0.8
335	5,300	1.5	1.3	56,300	5.2	2.9	+3.7	+0.9	90,500	6.2	4.3	+4.7	+3.4	139,200	11.0	4.4	+9.3	+3.5
336	4,100	4.9	2.6	40,500	2.9	1.3	-2.0	-1.1	65,300	7.8	3.6	-0.4	+1.8	102,900	10.1	3.5	+5.4	+1.8
337	12,200	4.4	1.4	46,600	7.4	1.3	+2.9	-0.3	77,300	1.4	0.5	-2.5	-0.4	124,600	7.5	2.0	+3.1	+0.6
Engine: Detroit Diesel 4R—71N (L33 HI Supercharged Vehicle: Bus																		
101	12,700	7.3	4.4	76,100*	11.7	8.1	+4.4	+1.7	79,100	26.5	20.7	+9.2	+6.3	124,*****	22.6	9.3	+6.3	+4.7
Average		4.3	2.4		4.7	2.5				8.4	4.7				9.5	4.6		
Mean Deviation		1.8	1.3		2.4	1.8				5.1	2.5				2.4	2.8		
Standard Deviation		2.2	1.6		3.1	2.2				4.8	3.2				1.8	2.9		
Coefficient of Variation		0.10	0.10		0.70	0.89				0.57	0.70				0.32	0.62		

*From Start-Assist limit.

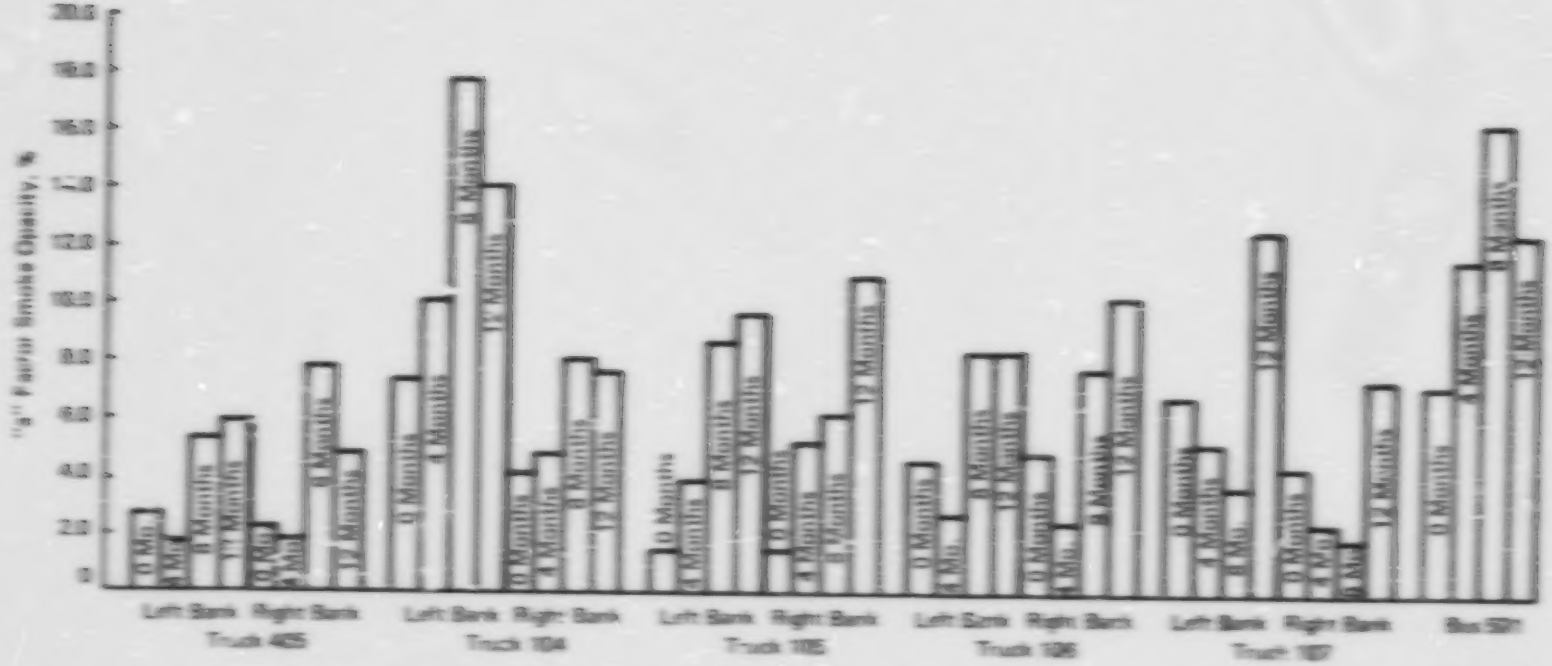


FIGURE 13. FEDERAL "a" FACTORS FOR SIX DETROIT DIESEL 6V-71N ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

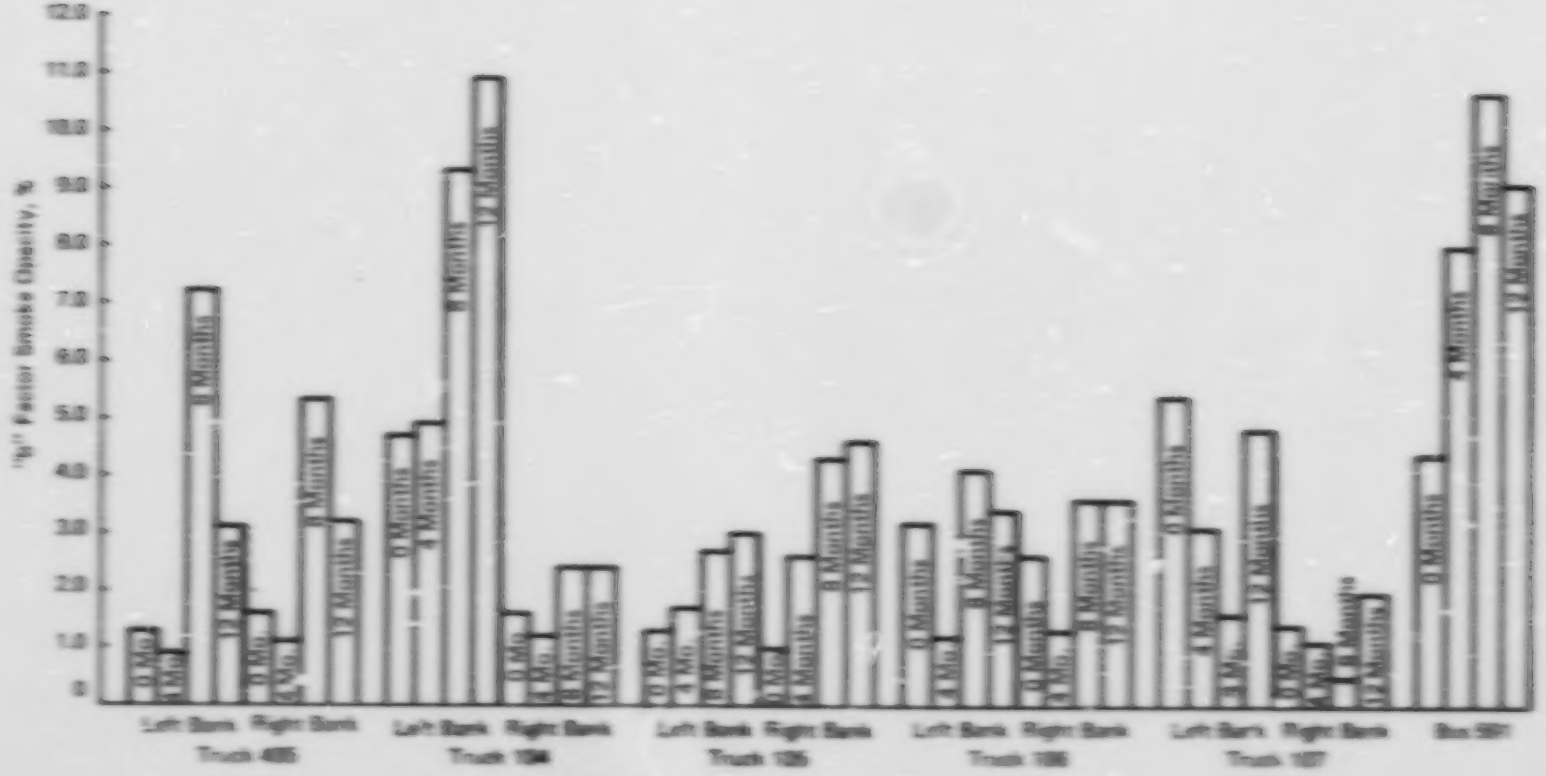


FIGURE 14. FEDERAL "b" FACTORS FOR SIX DETROIT DIESEL 6V-71N ENGINES TESTED AT 3, 4, 8, AND 12 MONTHS

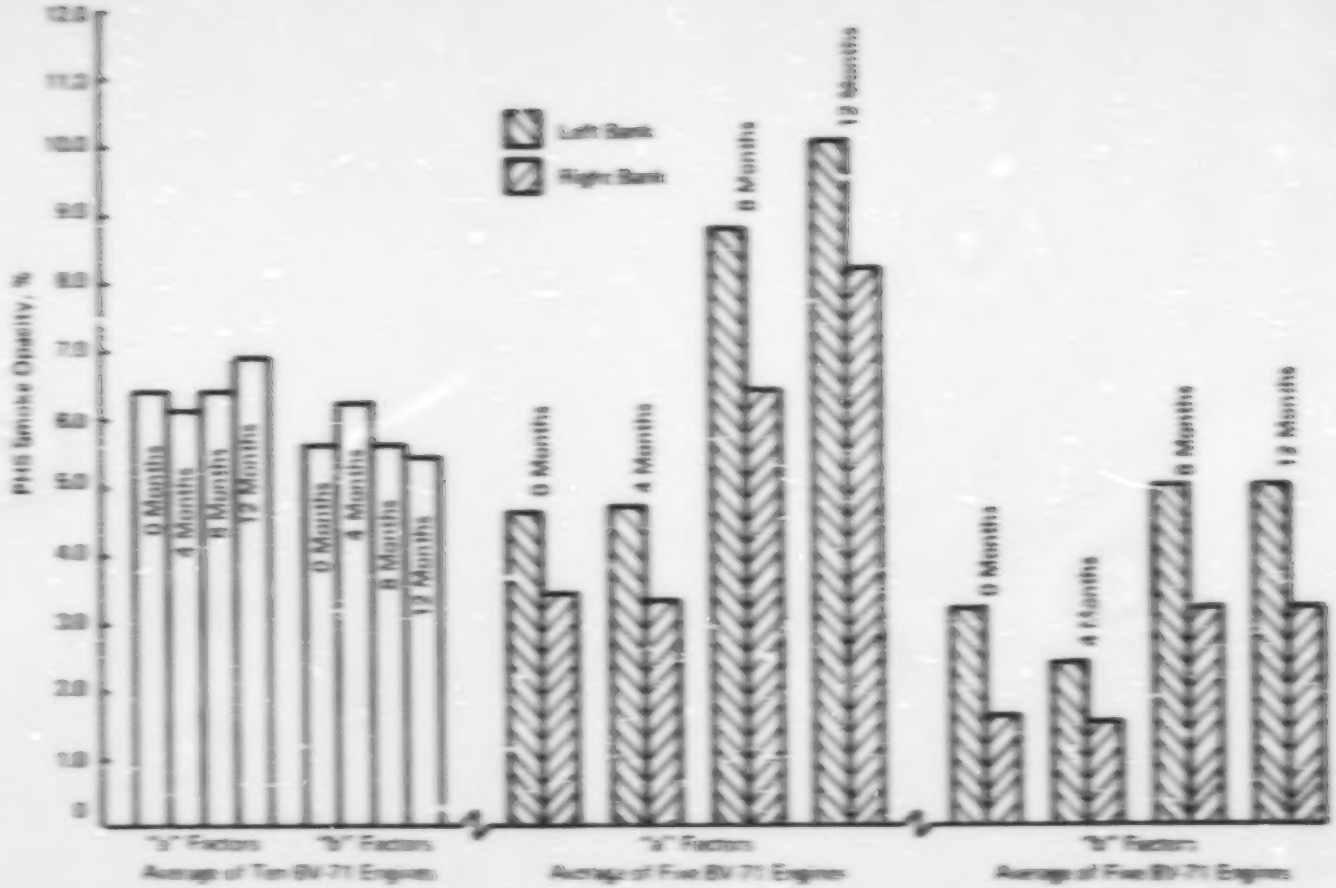


FIGURE 15. AVERAGE FEDERAL "a" AND "b" FACTORS FOR FIFTEEN DETROIT DIESEL "71" SERIES ENGINES

Factors consistently showed the most absolute variation, while the "b" Factors had the higher relative variation. The degree of absolute variation for both smoke factors increased at the second and third inspections, then decreased between the third and fourth tests. The relative variation for both factors increased at the second test, then decreased at the third and again at the fourth test. In general, these are similar to the trends in data variation for the 6V-71 bus engines. However, the 8V-71 engines had more relative and absolute data variation than the 6V-71 engines.

C. Four-Cycle Naturally Aspirated Engines in Intercity Service

Table 6 contains the data for this group of engines, which include Cummins NH-250 and V-903 models. This data is illustrated in Figures 14 to 20, inclusive.

1. Cummins NH-250 Engine

An important point should be noted concerning the NH-250 engines. At one time or other during the one-year test period, eight of the ten engines were running fuel delivery (rail) pressures some five to twenty psi (at 2100 rpm and maximum power) over the factory-specified 170 to 175 psi. Thus, these engines were fueled at a slightly higher rate than normal. Such an increase in fuel rate usually produces an increase in smoke opacity; however, the amount of this opacity increase cannot be accurately estimated from these surveillance-type tests. This observation, together with the fact that some of these engines had their rail pressures adjusted up or down during the test period, led to the conclusion that this data should be presented without special analysis or comments. This approach is further justified on the grounds that an unknown percentage of the NH-250 engines in use may have had their rail pressures adjusted--it is a very simple and inexpensive operation--at some time or other. The practice of some owners or operators of an NH-250-powered truck is to increase the fuel rate (and, hence, the horsepower) when the engine is new or newly rebuilt, then return the fuel rate to normal after a break-in period. Hence, the fleet vehicles powered by this engine are more or less representative of such trucks in normal operation.

The NH-250 engines initially demonstrated moderate to high smoke opacity, with "a" Factors from 7.3- to 17.7-percent opacity and "b" Factors from 10.9- to 22.4-percent opacity. One engine had a "b" Factor above the current (1970) limit of 20-percent opacity. Vehicle mileage at the first test ranged from 200 miles to 58,000 miles, and several other trucks had over 30,000 miles. However, the higher-mileage trucks did not necessarily have the highest smoke opacity. At the second- and third-round tests, the majority of the engines had increased opacity over baseline. Four engines had "b" Factors over the 20-percent opacity limit at each of these inspections. Note that the average smoke factors were higher than the baseline averages at the second and third tests (Figure 18).

TABLE 6. FOUR-CYCLE NATURALLY ASPIRATED ENGINES IN INTERCITY SERVICE

No.	Miles/Gallon	Direct-Acting Unit: PRD Driven Operators, %		Direct-Acting Unit: Differences*		Indirect-Acting Unit: PRD Driven Operators, %		Indirect-Acting Unit: Differences*		Direct-Acting Unit: PRD Driven Operators, %		Direct-Acting Unit: Differences*		Electric-Acting Unit: PRD Driven Operators, %		Electric-Acting Unit: Differences*	

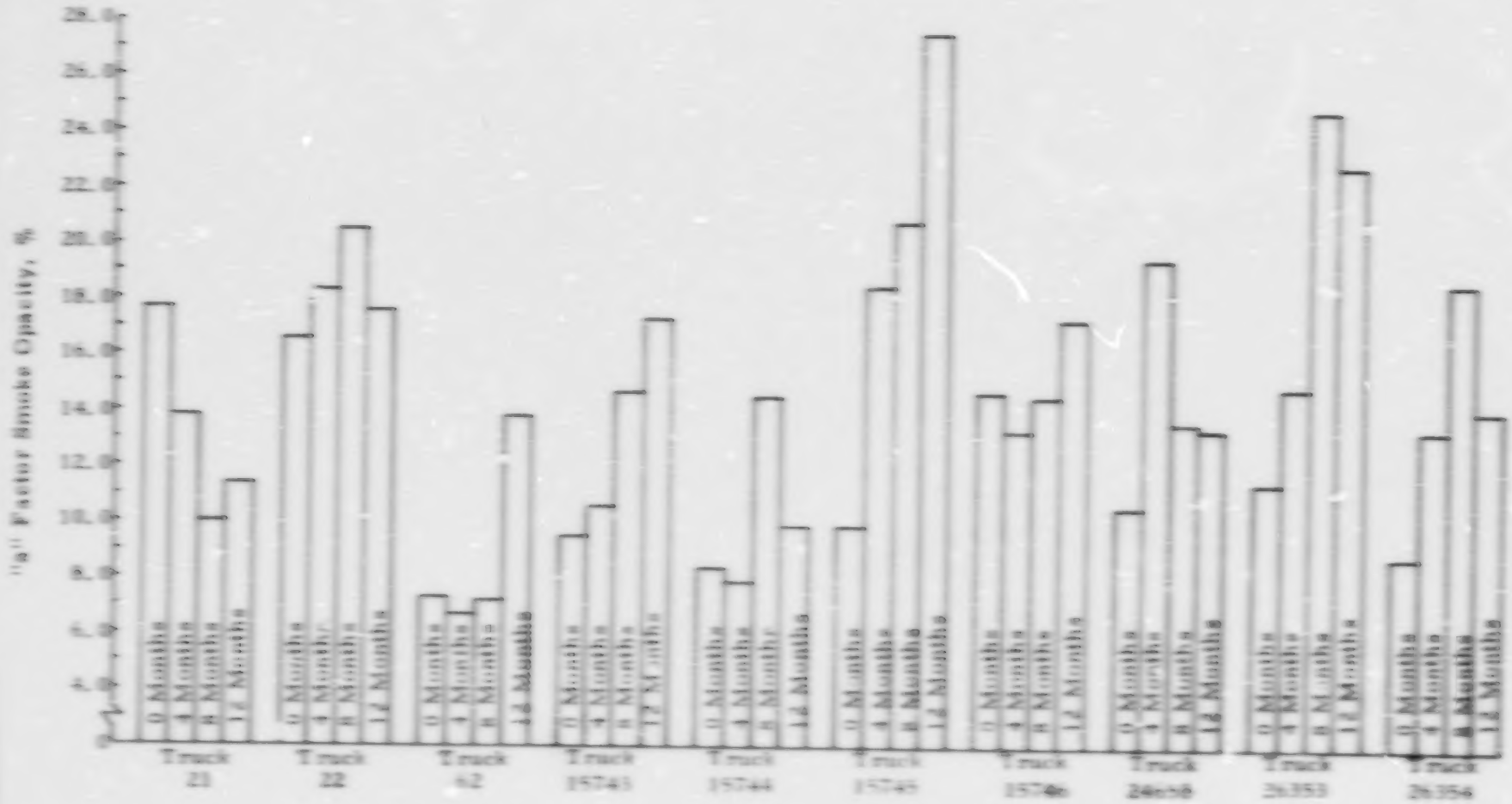


FIGURE 16. FEDERAL "a" FACTORS FOR TEN CUMMINS NH-250 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

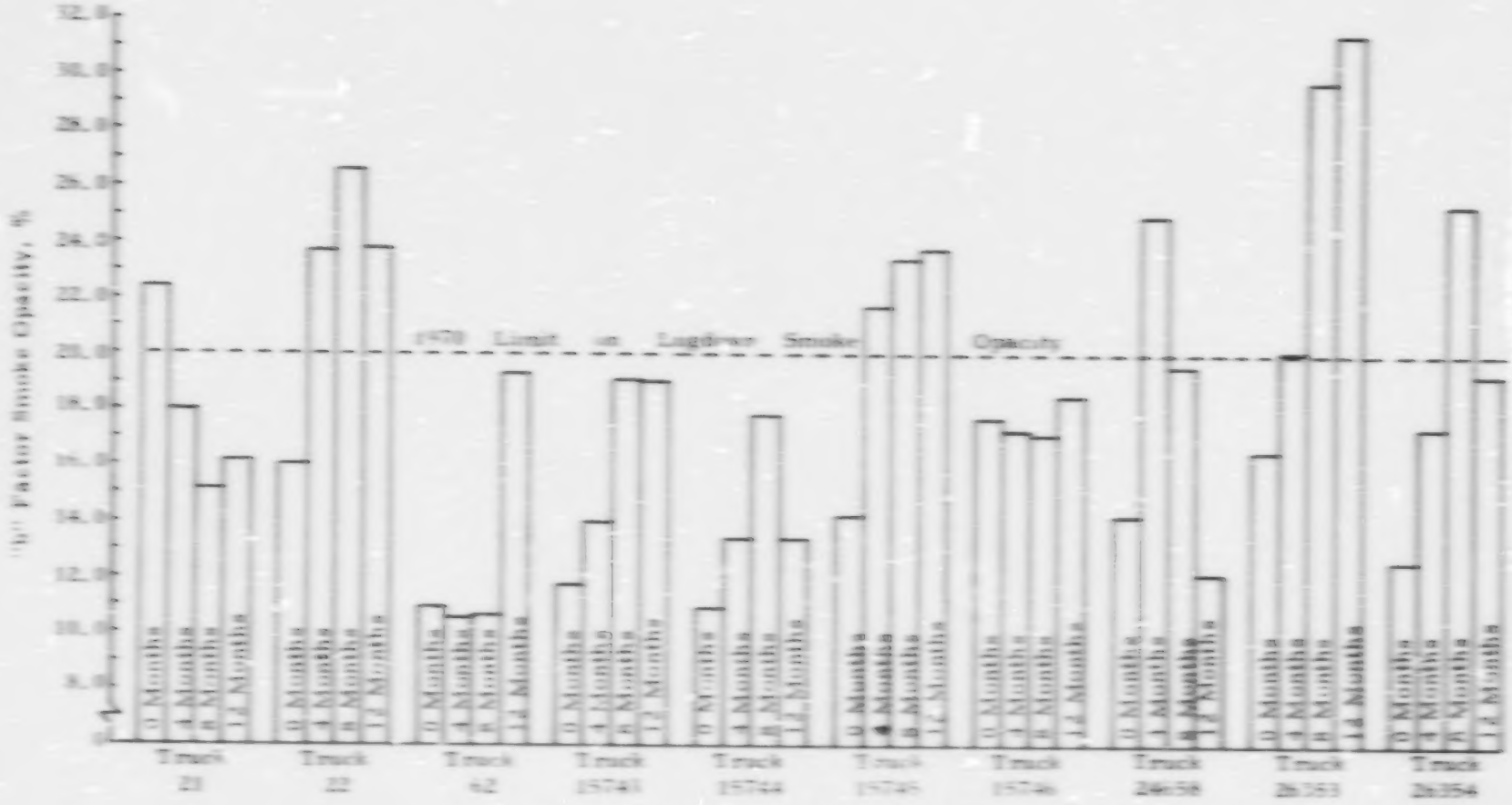


FIGURE 17. FEDERAL 'A' FACTORS FOR TEN CUMMINS 335-350 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

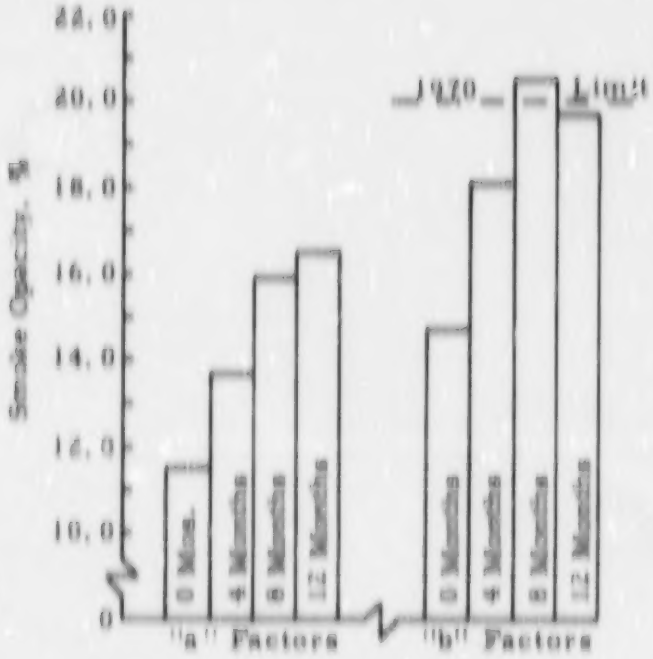


FIGURE 18. AVERAGE FEDERAL "a" AND "b" FACTORS FOR TEN CUMMINS NH-250 ENGINES

The fourth-round "a" Factors were in the range of 9.9- to 27.6-percent opacity and averaged 16.5-percent opacity. The corresponding "b" Factors ranged from 12.1- to 31.5-percent opacity and averaged 19.7-percent opacity. Three engines had "b" Factors over the certification limit. Elapsed test mileage after one year of operation was 50,300 to 129,500 miles, and total vehicle mileage at this point was 81,500 to 161,600 miles. None of these engines underwent any maintenance other than routine service.

Simple statistical analysis of these data shows that the dispersion about their respective means was quite large for a group of ten engines, and was much greater than for the two-cycle 6V and 8V engines. In general, the "b" Factors had the greatest amount of absolute dispersion (standard deviation) and the "a" Factors had the largest relative dispersion (coefficient of variation). Both types of dispersion tended to increase with time over the one-year period.

4. Cummins V-903 Engines

The V-903 engines included four 240-horsepower models with single

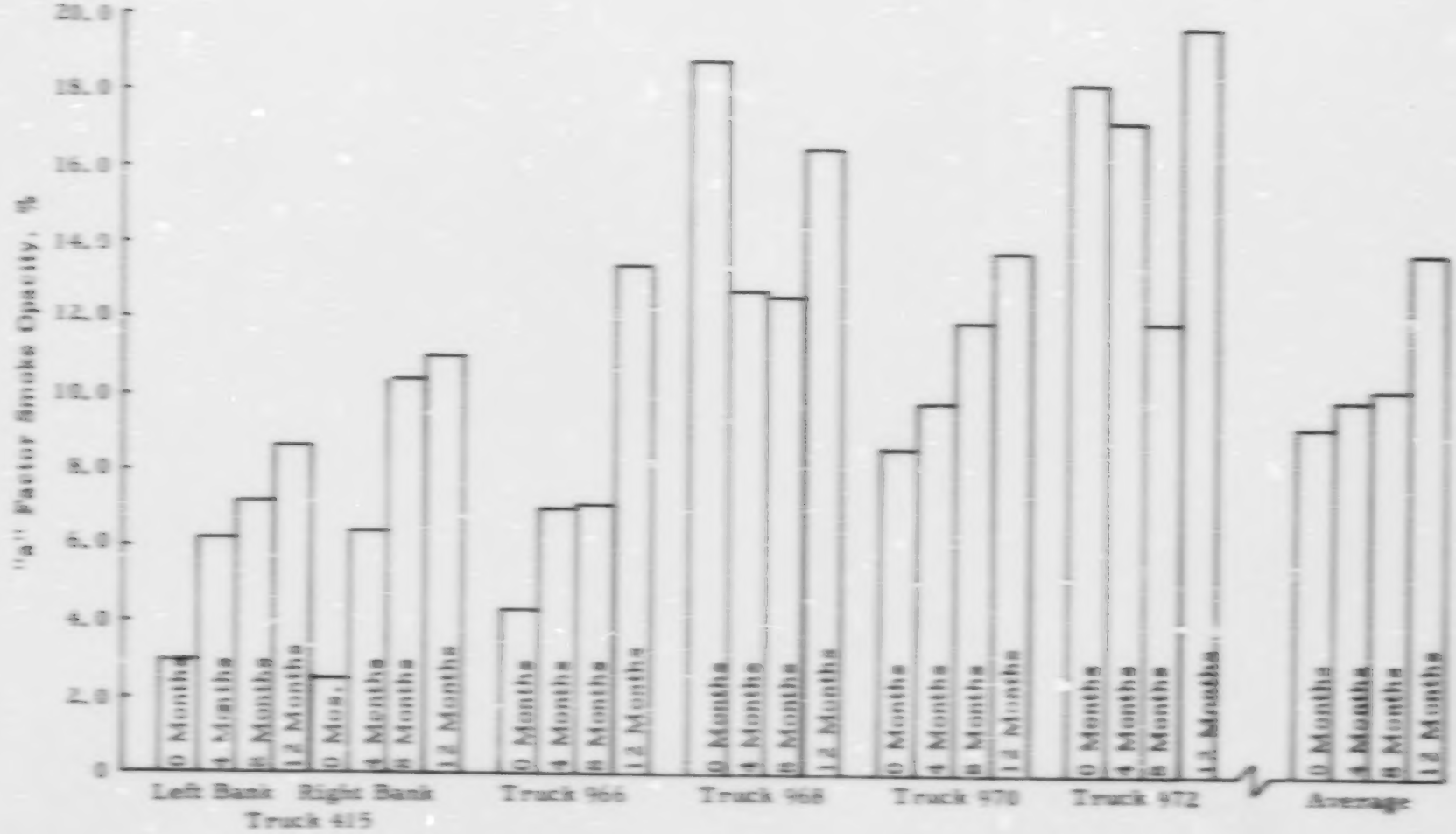


FIGURE 14. FEDERAL "a" FACTORS FOR FIVE CUMMINS V-903 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

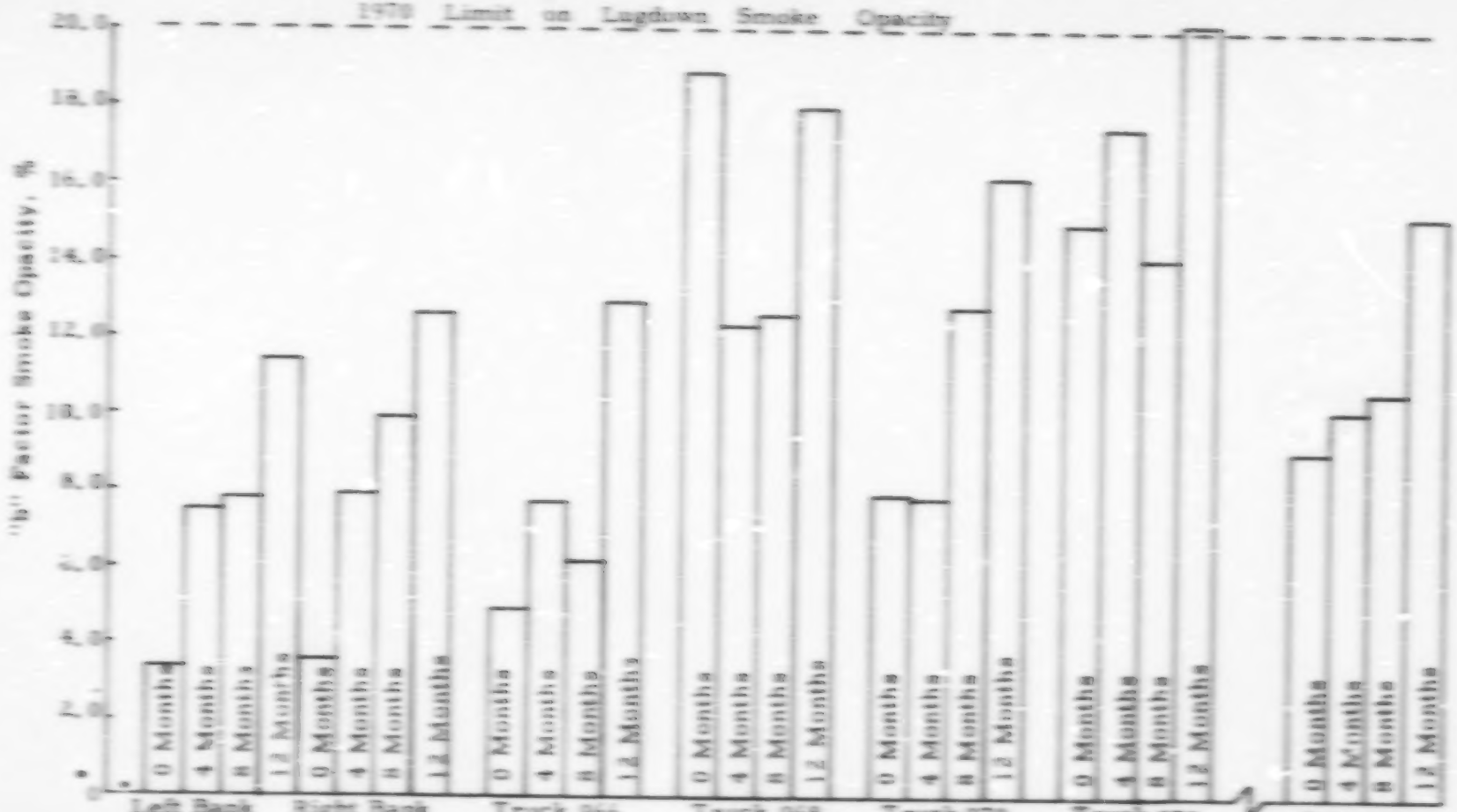


FIGURE 20. FEDERAL "b" FACTORS FOR FIVE CUMMINS V-903 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

exhaust outlet and one 320-horsepower model with dual isolated exhaust stacks. The 240-horsepower rating is obtained by speed derating a 280-horsepower model from 2600 rpm to 2400 rpm. The 240-horsepower rating at 2400 rpm is a standard Cummins option.

The five V-903 engines displayed a broad range of smoke opacities at the initial test, with "a" Factors ranging from 2.5- to 18.8-percent opacity and "b" Factors from 3.4- to 18.9-percent opacity. The average first-round smoke factors were about 9-percent opacity. Initial vehicle mileage was 800 to 13,500 miles. On the average, smoke opacity tended to increase slightly over baseline averages at the second and third tests. However, these slight changes in the average opacities were the result of some sharp individual increases and decreases cancelling each other out.

Fourth-round "a" Factors ranged from 8.6- to 19.7-percent opacity and averaged 13.8-percent opacity. The "b" Factors went from 11.4- to 20.2-percent opacity and averaged 15.2-percent opacity. Hence, one engine had lugdown smoke above the 20-percent opacity limit. Elapsed test mileage after one year was 98,500 to 149,800 miles, while total vehicle miles at the fourth test was 114,100 to 164,200. No engine maintenance of any consequence was performed during the test period.

The absolute and relative dispersion of these data was greatest at the initial inspection, decreased sharply at the second- and third-round tests, and increased somewhat at the final test. In all cases the "a" Factors appeared slightly more dispersed than the "b" Factors.

D. Four-Cycle Turbocharged Engines in Intracity Service

This group of engines includes five Mack ENDT 675 ("Maxidyne") engines and two Mack ENDT 673B engines. The 675 engines powered commercial garbage disposal trucks of a very large and heavy type, while the 673B engines were in small single axle truck-tractors. The data for these engines are presented in Table 7 and illustrated in Figures 21 to 23.

1. Mack ENDT 675 Engines

The Maxidyne engines had smoke output typical of most turbocharged engines, i.e., high smoke peaks during acceleration and low smoke opacity under high power steady-state (or quasi-steady-state) operation. First-round "a" Factors were 14.8- to 25.6-percent opacity, with an average value of 19.2, while the "b" Factors ranged from 4.1- to 12.0-percent opacity and averaged 7.4. Four of the garbage trucks had low initial mileage (1400 to 5000 miles) and one had over 28,500 miles. Again, the vehicle with the highest mileage did not have the highest smoke factors. The second-round test revealed that three engines had smoke factors substantially higher than baseline. Average "a" and "b" Factor values were 27.0- and 10.1-percent

TABLE 7. FOUR-CYCLE TURBOCHARGED ENGINES IN INTRACITY SERVICE

No.	Initial Mileage	Front-Axle Tire: 1/32" Factor	Front-Axle Tire: In. Factor	Dropout Tract Miles	Second-Axle Tire: 1/32" Factor	Second-Axle Tire: In. Factor	Second-Axle Tire: Difference*: 1/32"	Second-Axle Tire: Difference*: In.	Dropout Tract Miles	Third-Axle Tire: 1/32" Factor	Third-Axle Tire: In. Factor	Third-Axle Tire: Difference*: 1/32"	Third-Axle Tire: Difference*: In.	Dropout Tract Miles	Fourth-Axle Tire: 1/32" Factor	Fourth-Axle Tire: In. Factor	Fourth-Axle Tire: Difference*: 1/32"	Fourth-Axle Tire: Difference*: In.
Engine: Mack E6E7-V71																		
Vehicle: Commercial Carriage Trucks																		
1	1,000	77.2	6.7	42,400	82.3	11.1	+53.3	+4.4	12,587	84.9	78.8	+45.7	+8.4	41,523	86.7	13.3	+44.3	+7.3
2	26,000	85.1	5.4	42,388	83.7	9.8	+5.6	+4.3	36,350	84.8	84.3	+45.7	+4.6	42,998	85.1	11.4	+46.2	+4.3
3	1,000	83.6	62.0	5,000	82.8	7.8	-0.2	+6.2	17,970	83.8	83.3	+6.2	+5.7	32,987	85.8	84.8	+6.2	+1.2
4	5,000	84.8	4.1	4,987	87.3	85.8	+22.8	+6.7	35,472	79.8	7.4	+25.8	+3.1	35,000	87.4	82.6	+22.8	+8.5
5	1,000	86.1	5.4	5,786	89.9	11.0	+53.3	+5.6	38,756	84.0	86.1	+25.7	+2.9	46,734	85.2	9.5	+7.2	+46.0
Average		81.2	7.34		77.0	86.1				81.5	83.75				86.91	82.75		
Mean Deviation		3.8	2.7		3.2	1.3				4.75	2.45				1.46	1.1		
Standard Deviation		4.1	3.2		4.2	1.4				7.34	4.1				1.48	1.31		
Coefficient of Variation		4.21	5.40		5.37	5.34				5.34	5.29				5.36	5.73		
Engine: Mack E6E7-V76																		
Vehicle: Truck-Tractor																		
60025	4,394	75.0	7.4	4,794	77.4	82.8	+1.2	+5.8	7,386	80.1	86.0	+7.4	+5.8	42,736	82.4	86.8	+4.8	+7.8
60026	4,456	7.7	6.1	4,486	82.9	6.7	+2.8	+5.2	8,356	86.2	8.5	+6.8	+2.8	11,975	86.7	12.8	+4.8	+5.8
Average		11.4	7.8		86.5	11.2				86.4	11.2				86.57	79.84		

*From first-recorded test.

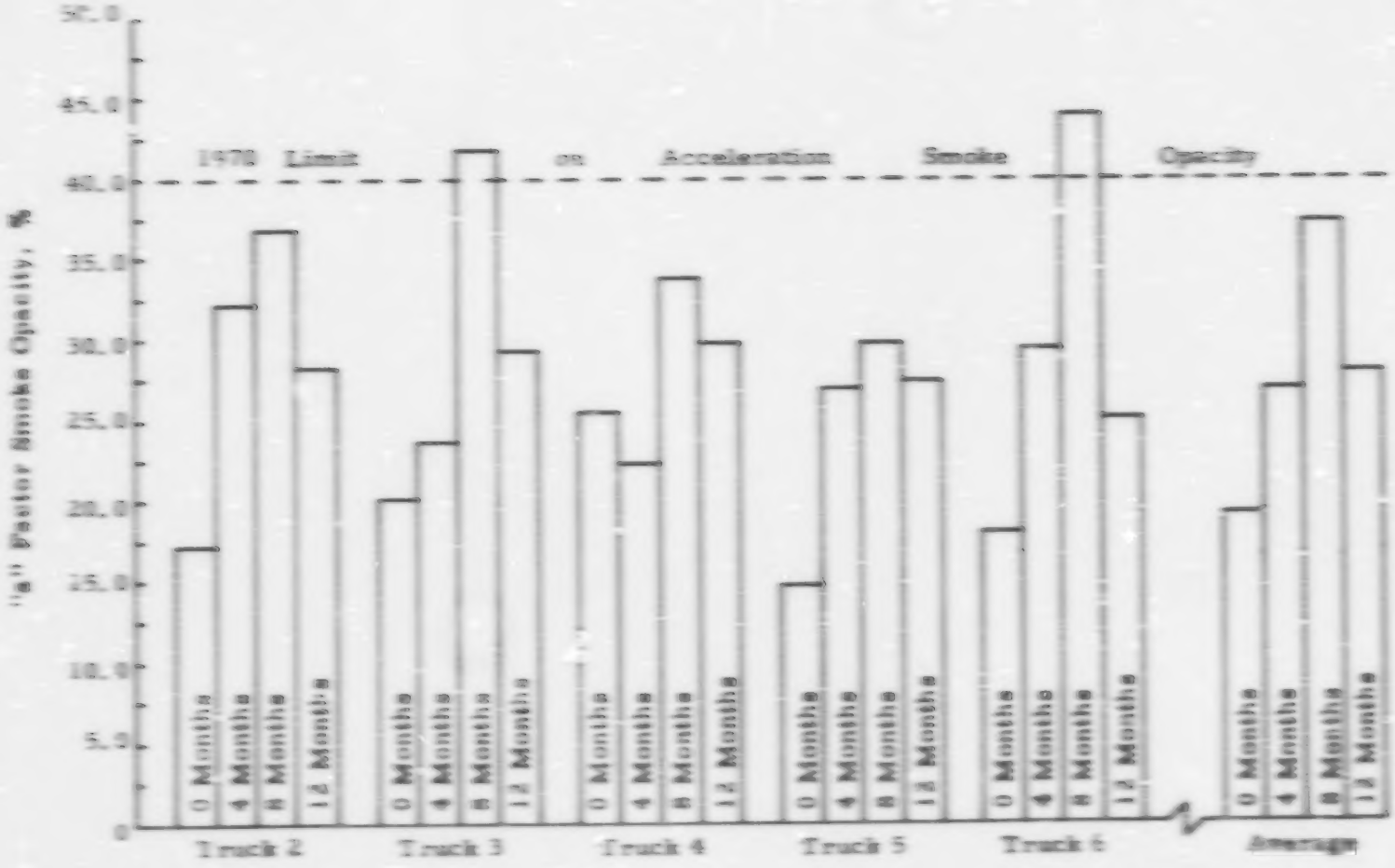


FIGURE 21. FEDERAL "a" FACTORS FOR FIVE MACK ENDT 675 ENGINES TESTED AT 0, 4, 9, AND 12 MONTHS

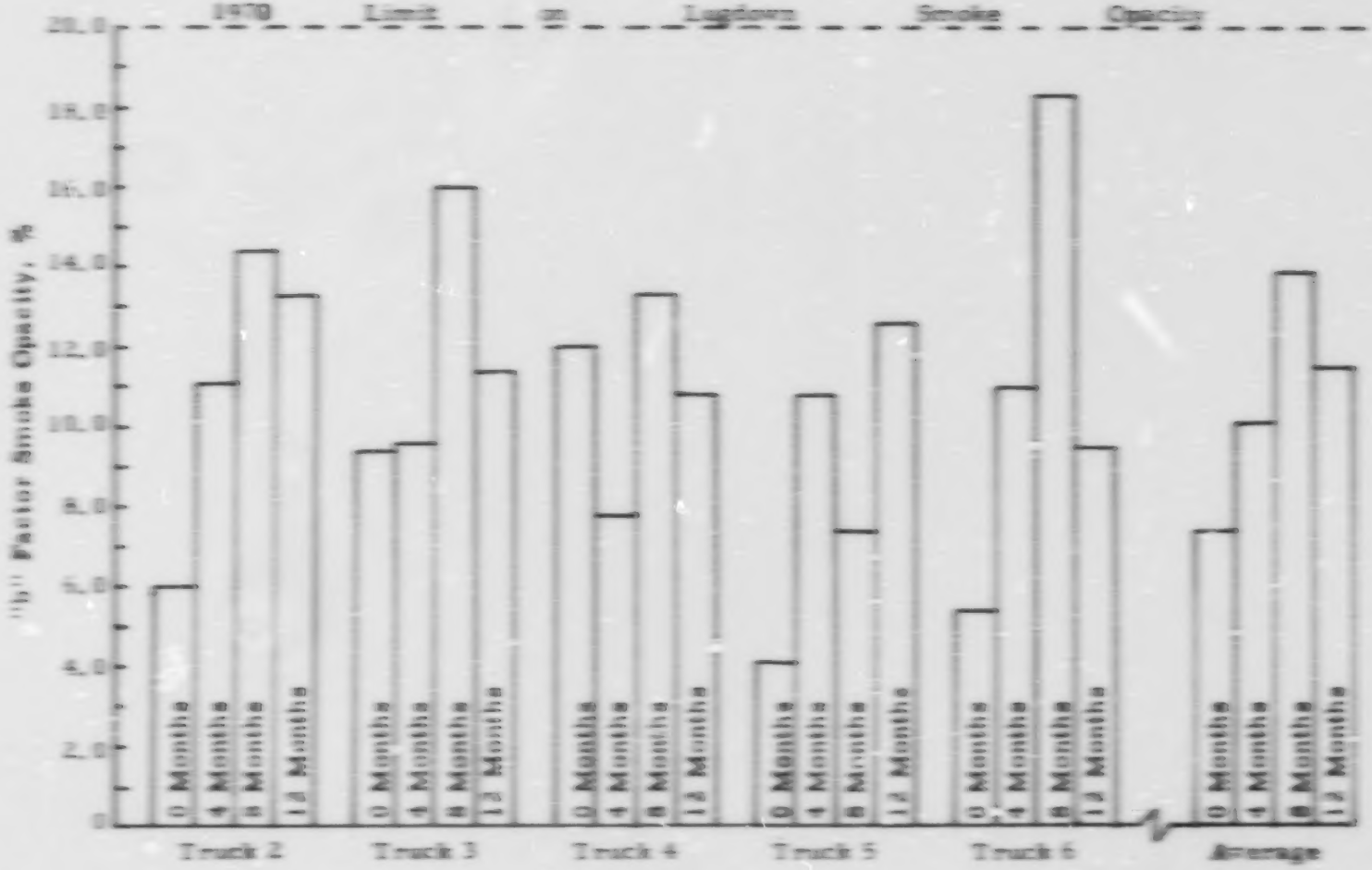


FIGURE 22. FEDERAL "S" FACTORS FOR FIVE MACK ENDT 675 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

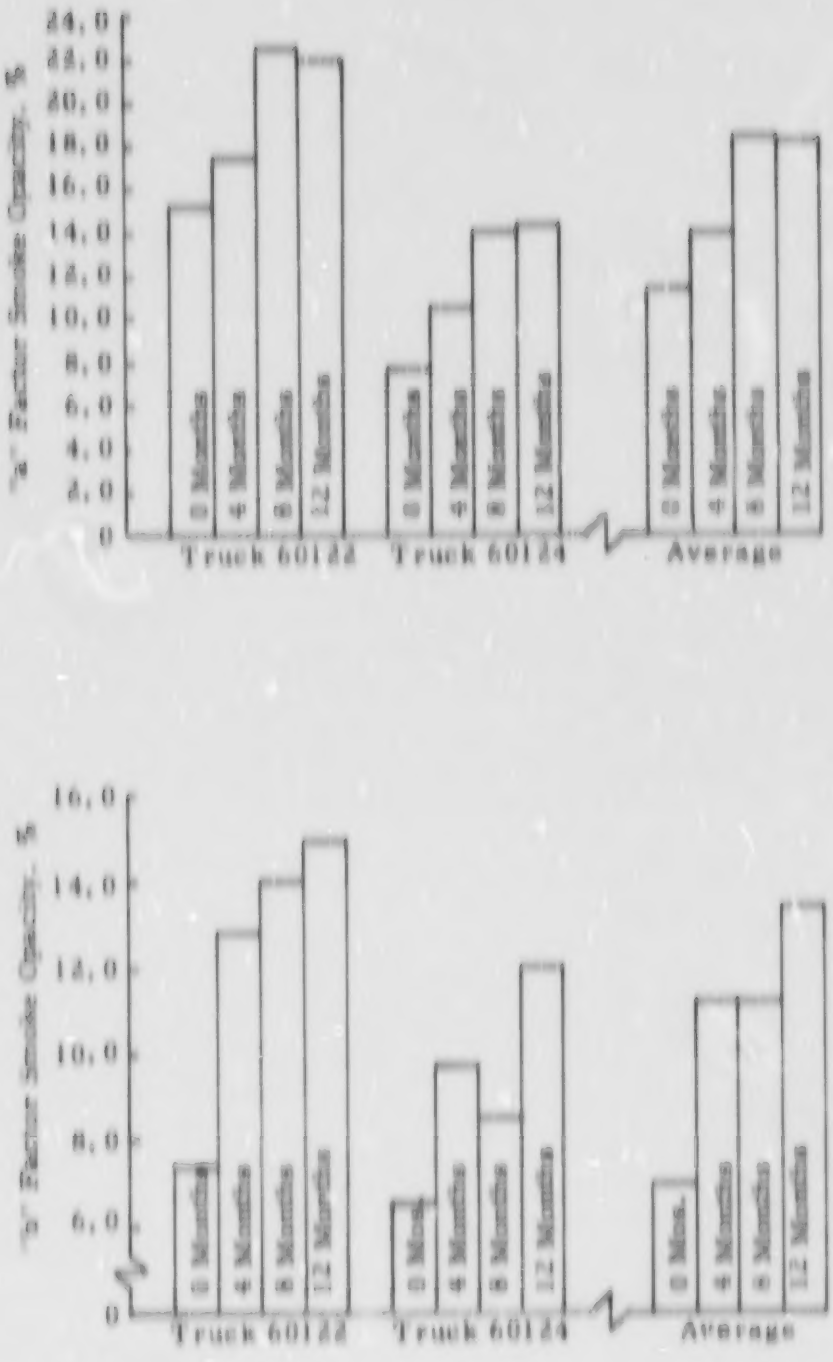


FIGURE 25. FEDERAL "a" AND "b" FACTORS FOR TWO MACK ENDT 673B ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

opacity, respectively. Similar -- and even larger -- increases over baseline opacities were observed at the third inspection. Third-round "a" Factors ranged from approximately 30- to 44-percent opacity, with two engines over the 40-percent opacity certification limit. The average "a" Factor was 37.3-percent opacity. The average "b" Factor value was 13.9-percent opacity. Hence, the third-round averages were almost double the first-round averages.

However, three engines had marked decreases in smoke opacity between the third and fourth inspections. Fourth-round "a" Factors were 25.2- to 29.8-percent opacity, and averaged 28.0, while "b" Factors ranged from 9.5- to 13.3-percent opacity and averaged 11.5. Elapsed test mileage for one year was 30,000 to 44,000 miles, and total vehicle mileage at the last inspection was 52,300 to 71,400 miles. While these mileage figures are not high when compared to those of the intercity vehicles, the garbage trucks are subjected to very severe service, and mileage is therefore not an indication of the wear-and-tear on the engines.

The simple statistical analysis performed on these data shows that the "a" Factors had a high degree of absolute dispersion at the first three tests, but very little at the last inspection, while the "b" Factors were highly dispersed at the first- and third-round tests and more closely grouped at the second and fourth tests. The relative dispersion of the data followed similar trends.

2. Mack ENDT 673B Engines

The two 673B engines had first-round "a" Factor values of 15.2- and 7.7-percent opacity, and "b" Factor values of 7.4- and 6.5-percent opacity. Initial vehicle mileages were about 4800 and 6300 miles. Smoke opacity at the three subsequent inspections was higher than baseline for both engines. Fourth-round "a" Factors were 22.0- and 14.3-percent opacity, and "b" Factors were 14.9- and 12.0-percent opacity. Elapsed test mileage after one year was 10,700 to 11,900 miles, and total vehicle mileage was 16,800 and 17,000.

The average "a" Factor increased steadily over the baseline average at the second and third tests, then remained almost constant at the third and fourth tests. The average "b" Factor increased sharply over the baseline average at the second inspection, remained constant at the third test, and increased slightly between the third and fourth tests.

E. Four-Cycle Turbocharged Engines in Intercity Service

This group included two Mack ENDT 675 engines and four Cummins NTC-335 engines. However, one of the Cummins-powered trucks was deleted from the project following the second-round test. The reason for this deletion was the sale of the truck and its subsequent move to Dallas.

The Cummins engines tested were of two types, one with 335 horsepower and the other with 280 horsepower. The only difference in the two engines is their fuel rate.

1. Mack ENDT 675 Engines

The two-truck-tractors powered by Maxidyne engines came into the project with high mileage, over 67,000 and 70,000 miles, respectively. The first-round "a" Factors (Table 8 and Figure 24) were 26.5- and 28.7-percent opacity, and the corresponding "b" Factors were only 7.6- and 6.3-percent opacity. Second-round smoke opacity was considerably higher than baseline, and one "a" Factor was over the 40-percent opacity limit. A sharp drop in opacity occurred between the second and third inspections, but the smoke factors were still above baseline values. The opacity decreases were due to engine tune-ups performed at approximately 125,000 odometer miles. Such a tune-up usually consists of removing and cleaning injectors, setting valve clearances and injection timing, and adjusting the injection pump to obtain proper fuel delivery rate.

Fourth-round "a" Factors were 44.9- and 36.8-percent opacity, with an average of 40.8, while "b" Factors were 13.6- and 10.5-percent opacity and averaged 12.0. Elapsed test mileage was 137,700 and 124,400, and total vehicle mileage at the end of the test was 205,100 and 194,700.

2. Cummins NTC-335 Engines

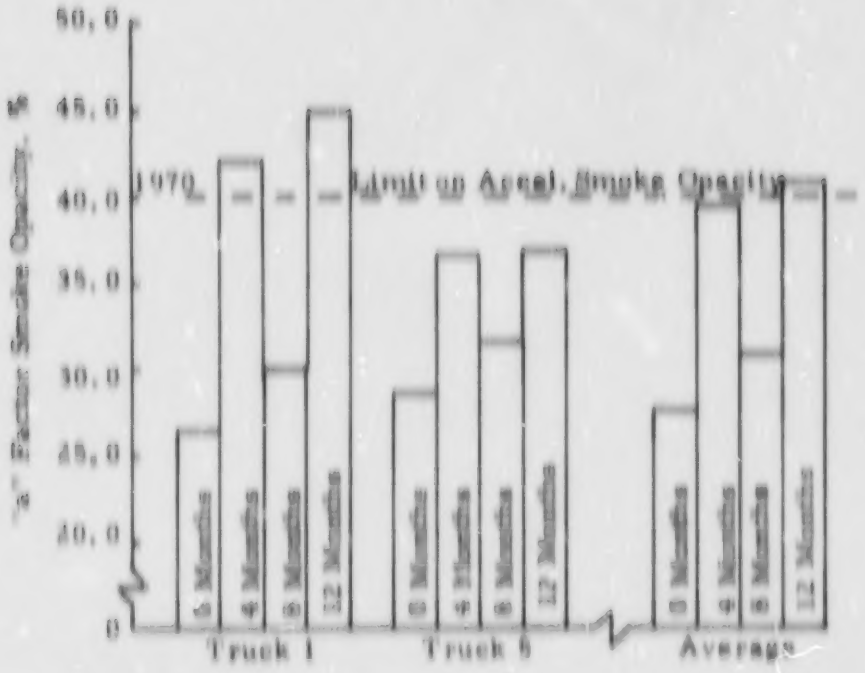
Three of the four turbocharged NTC-335 engines had first-round "a" Factors under 10-percent opacity, while the remaining engine was at almost 25-percent opacity (Figure 25). This engine was running with increased fuel pump pressure, similar to several of the Cummins NH-250 engines. However, the "b" Factors were all very low, from 3.1- to 4.1-percent opacity (Figure 26). Average first-round "a" and "b" Factors were 12.0 and 3.6, respectively. Initial vehicle mileage ranged from 18,600 to 87,400 miles. Smoke opacity generally increased between the first and second inspections, then decreased between the second and third tests. One of the decreases noted at the third-round test was due to tune-up, similar to that previously described, at about 130,000 odometer miles (Truck No. 458). However, the average "a" and "b" Factors at the second and third tests were still slightly higher than at baseline.

Fourth-round "a" Factors were 10.1- to 17.2-percent opacity, and the average was 13.9. These are considered to be low values for turbocharged engines. "b" Factors were also low, ranging from 6.3- to 7.3- percent opacity and averaging just 6.7. Elapsed test mileage for the one-year period was 96,200 to 131,800 miles, and total vehicle mileage at the last test was 128,600 to 219,200.

TABLE 8. FOUR-CYCLE TURBOCHARGED ENGINES IN INTERCITY SERVICE

No.	Model Year Average	Four-Stroke Cycle 1992 Detroit Diesel Corp.		Current Total Miles	Six-Stroke Cycle 1992 Cummins Diesel, N				Current Total Miles	Ten-Stroke Cycle 1992 Detroit Diesel, N				Current Total Miles	Four-Stroke Cycle 1992 Cummins Diesel, N			
							Difference*					Difference*					Difference*	
		1st Rebuild	2nd Rebuild		1st Rebuild	2nd Rebuild	At 1st	At 2nd		1st Rebuild	2nd Rebuild	At 1st	At 2nd		1st Rebuild	2nd Rebuild	At 1st	At 2nd
Engine: Model 8V92TA Vehicle: Coach-Tractor																		
1	1992	25.0	7.5	42,700	42.0	22.8	+16.7	+1.5	96,000	50.0	12.5	+2.5	+0.5	220,000	48.7	23.6	+23.6	+4.2
2	1992	28.7	6.5	42,000	36.7	22.8	+8.0	+7.3	82,000	51.4	9.2	+2.4	+2.7	228,000	35.8	20.5	+8.0	+6.0
Average		27.0	7.0		39.4	22.7				50.8	10.8				42.3	22.0		
Engine: Cummins NTC-370 Vehicle: Coach-Tractor																		
21	1991	14.9	5.5	46,300	7.5**	4.5	+6.9	+6.8	86,200*	12.7	7.2*	+8.8	+6.5	200,000	16.8	6.8	+7.8	+5.5
148	1992	7.5	5.0	16,200	6.8	3.8	+0.7	--	--	--	--	--	--	--	--	--	--	--
156	1992	28.8	6.1	11,900	28.7	5.8	+6.1	+7.8	80,000*	36.8	8.9	+7.8	+6.8	180,000	37.5	6.7	+7.8	+6.8
1211	1992	12.9	5.7	12,900	15.4	6.8	+2.9	+2.7	76,000	22.9	6.5	+2.8	+2.8	90,200	28.5	7.5	+8.8	+8.8
Average		15.8	5.8		15.5	6.7				18.8	6.2				22.9	6.7		

*Four-Stroke Cycle.
**Reduction Assembly Front Load Gear.



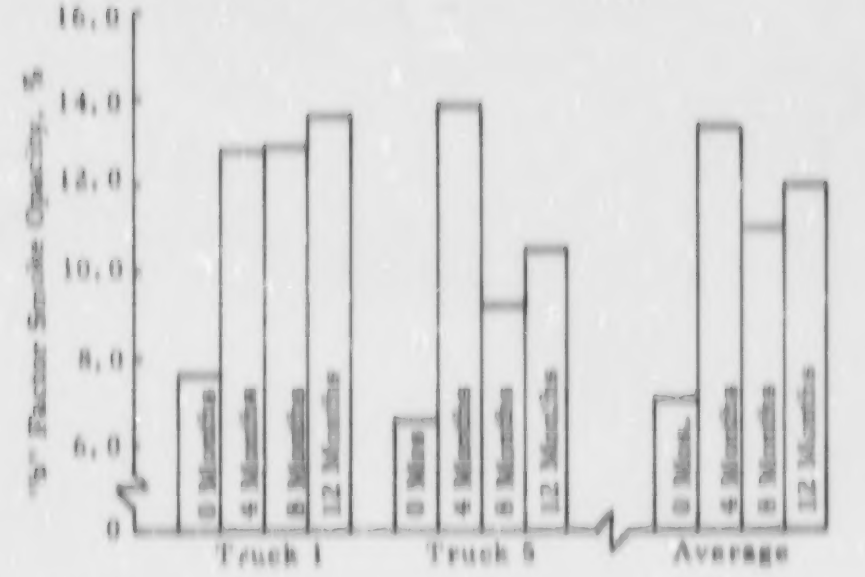


FIGURE 24. FEDERAL "a" AND "b" FACTORS FOR TWO MACK ENDT 675 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

FIGURE 15. FEDERAL "a" FACTORS FOR FOUR COMMONS NTC-335 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

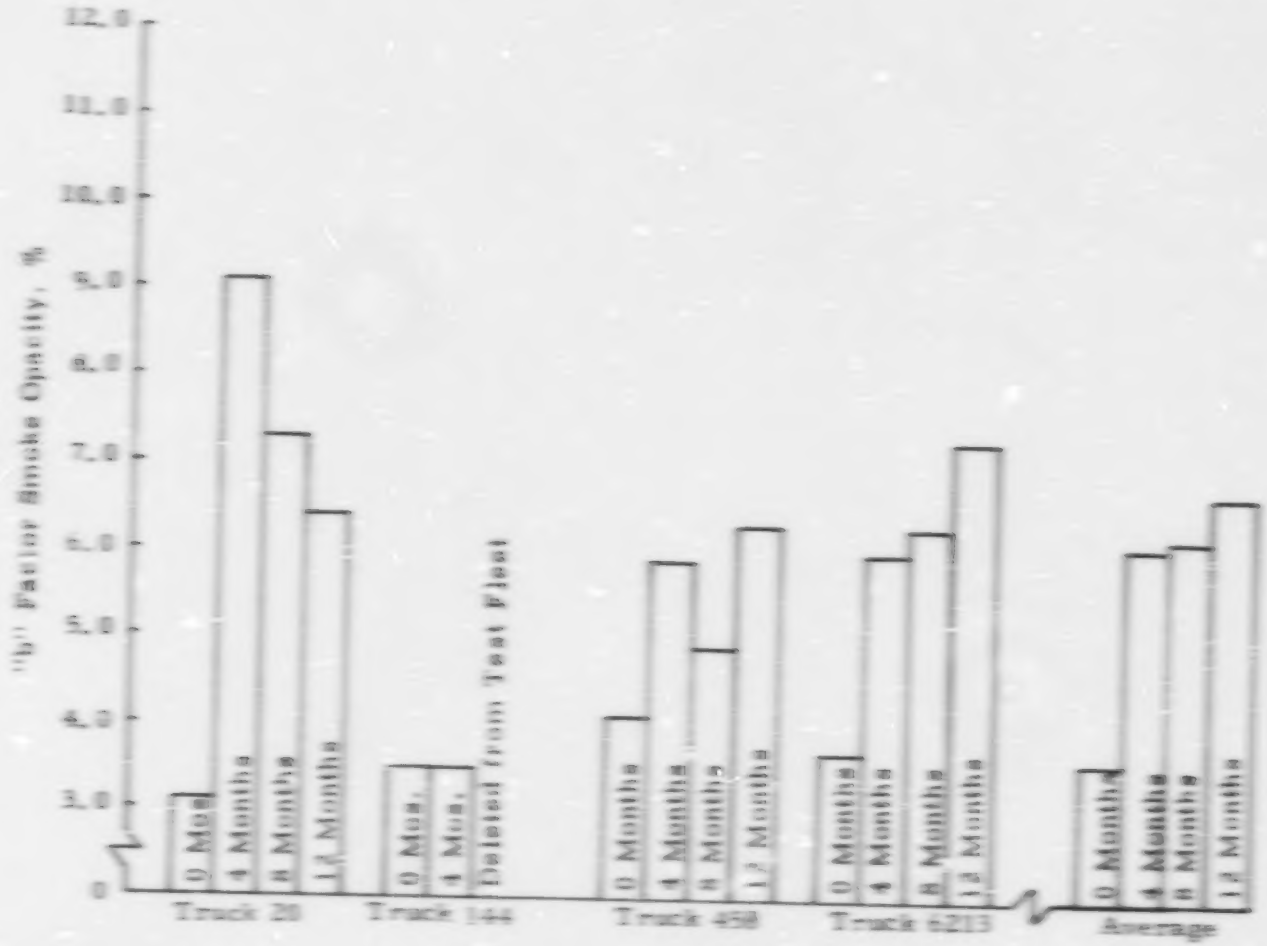


FIGURE 24. FEDERAL "b" FACTORS FOR FOUR CUMMINS NTC-335 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

F. Midrange Two-Cycle And Four-Cycle Engines in Intracity Service

Five groups of engines are included under this general classification. These engines are smaller and less powerful, and operate at higher crankshaft speeds, than the engines discussed previously. The data for the first four tests of these engines are presented in Table 9.

1. Caterpillar 1145 Engines

The Caterpillar 1145 engines generally had low smoke opacity at their initial test. The "a" Factors (Figure 27) ranged from 13.0- to 16.2-percent opacity and averaged 14.6. There was a very brief smoke peak of 50- to 70-percent opacity during the first acceleration of the smoke test cycle. However, the brief duration of this peak allowed the "a" Factor, which is a time-averaged quantity, to remain fairly low. The "b" Factors (Figure 28) were 8.5- to 14.5-percent opacity, with an average value of 10.7. The initial mileage of the vehicles was 2,000 to 5,800 miles.

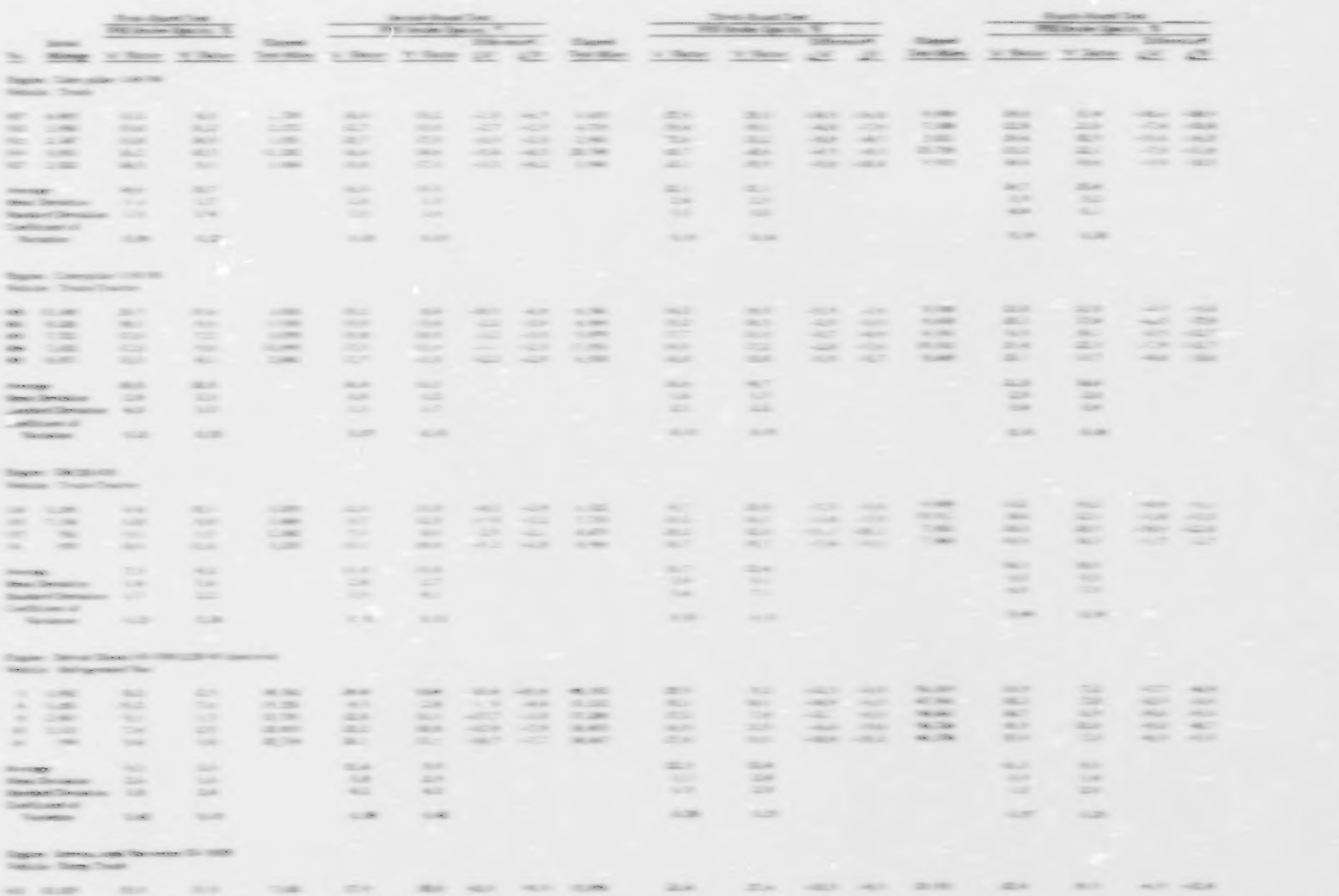
Smoke opacity was generally increased over baseline at the second inspection. Average second-round "a" and "b" Factors were 16.9- and 15.5-percent opacity, respectively. A further increase in opacity was noted at the third-round test, where the average "a" and "b" Factors were 22.1 and 21.1, respectively. Two engines had "b" Factors above 20-percent opacity. For the fourth-round test, "a" Factors ranged from 18.4- to 29.6-percent opacity and averaged 24.7, while "b" Factors were 19.6 to 33.4, with an average of 25.4. Four of the five "b" Factors were above the 20-percent opacity limit. Elapsed test mileage was quite varied, with a low of 3,000 miles and a high of 25,700, and total vehicle mileage at the last test was 7,300 to 31,500.

2. Caterpillar 1150 Engines

These engines had first-round "a" Factors of 15.5- to 25.7-percent opacity (Figure 29) and "b" Factors from 7.0- to 15.6-percent opacity (Figure 30). The average "a" and "b" values were 18.8 and 10.0, respectively. As in the case of the Cat 1145 engines, there was a brief smoke peak during the initial acceleration of the test. This peak was of 75- to 95-percent opacity, but its effect on the time-averaged "a" Factors was small. Vehicle mileage at the initial test was 7,600 to 13,100 miles.

Second-round "a" Factors were generally lower than at the initial test, while "b" Factors were slightly higher. One engine (in Truck No. 880) received an adjustment to its injection pump after the first-round test and showed greatly decreased smoke opacity at the second inspection. The "a" Factors ranged from 15.2- to 17.7-percent opacity, and averaged 16.4, while "b" Factors were 8.8 to 13.4, and averaged 11.1. Third-round "a" and "b" Factors were slightly higher than at the second test, and averaged 16.6- and 14.7-percent opacity, respectively.

TABLE 9. MIDRANGE TWO-CYCLE AND FOUR-CYCLE ENGINES IN INTRACITY SERVICE



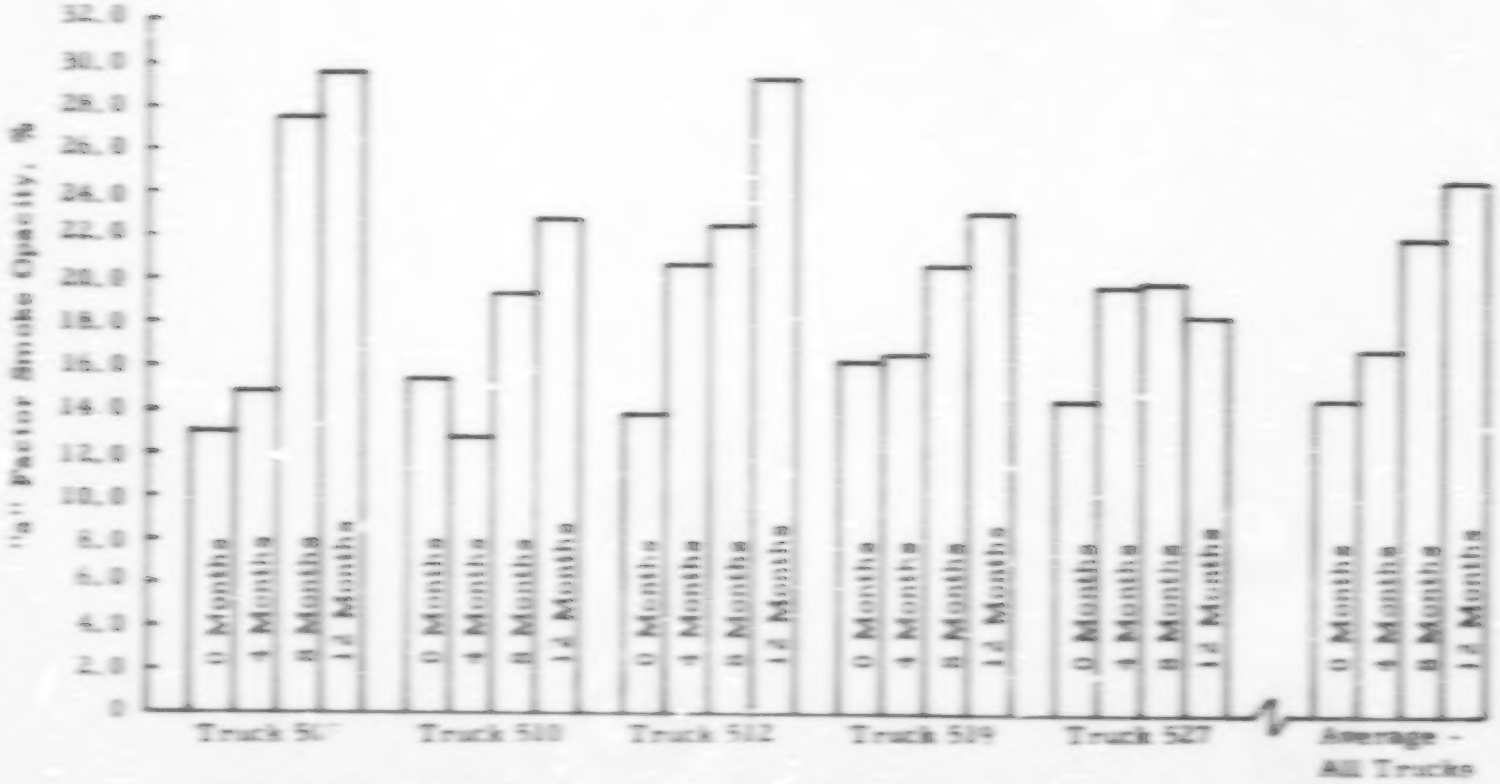


FIGURE 47. FEDERAL "a" FACTORS FOR FIVE CATERPILLAR 1145 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

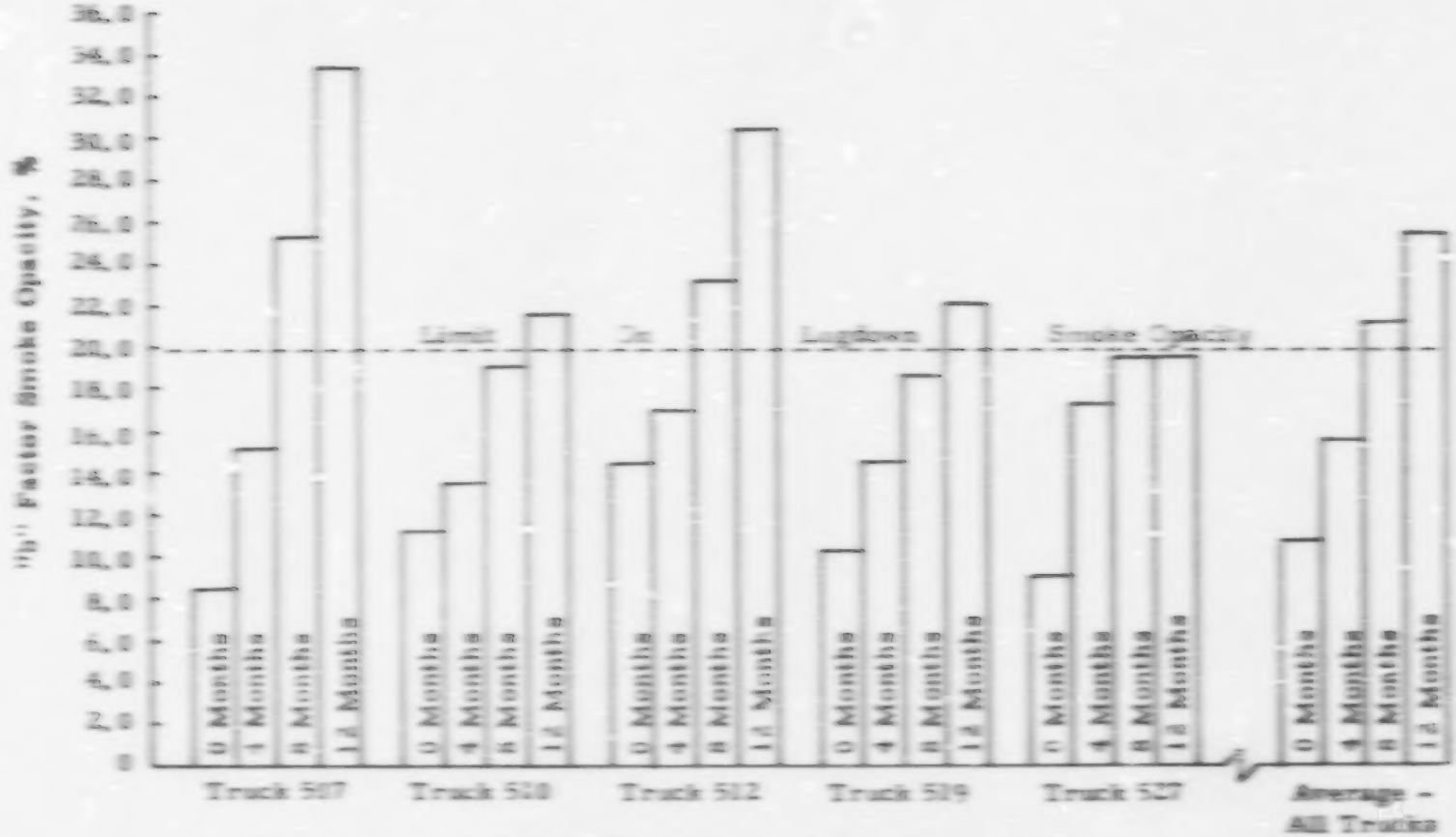


FIGURE 28. FEDERAL "b" FACTORS FOR FIVE CATERPILLAR 1145 ENGINES TESTED AT 0, 4, 8, and 12 MONTHS

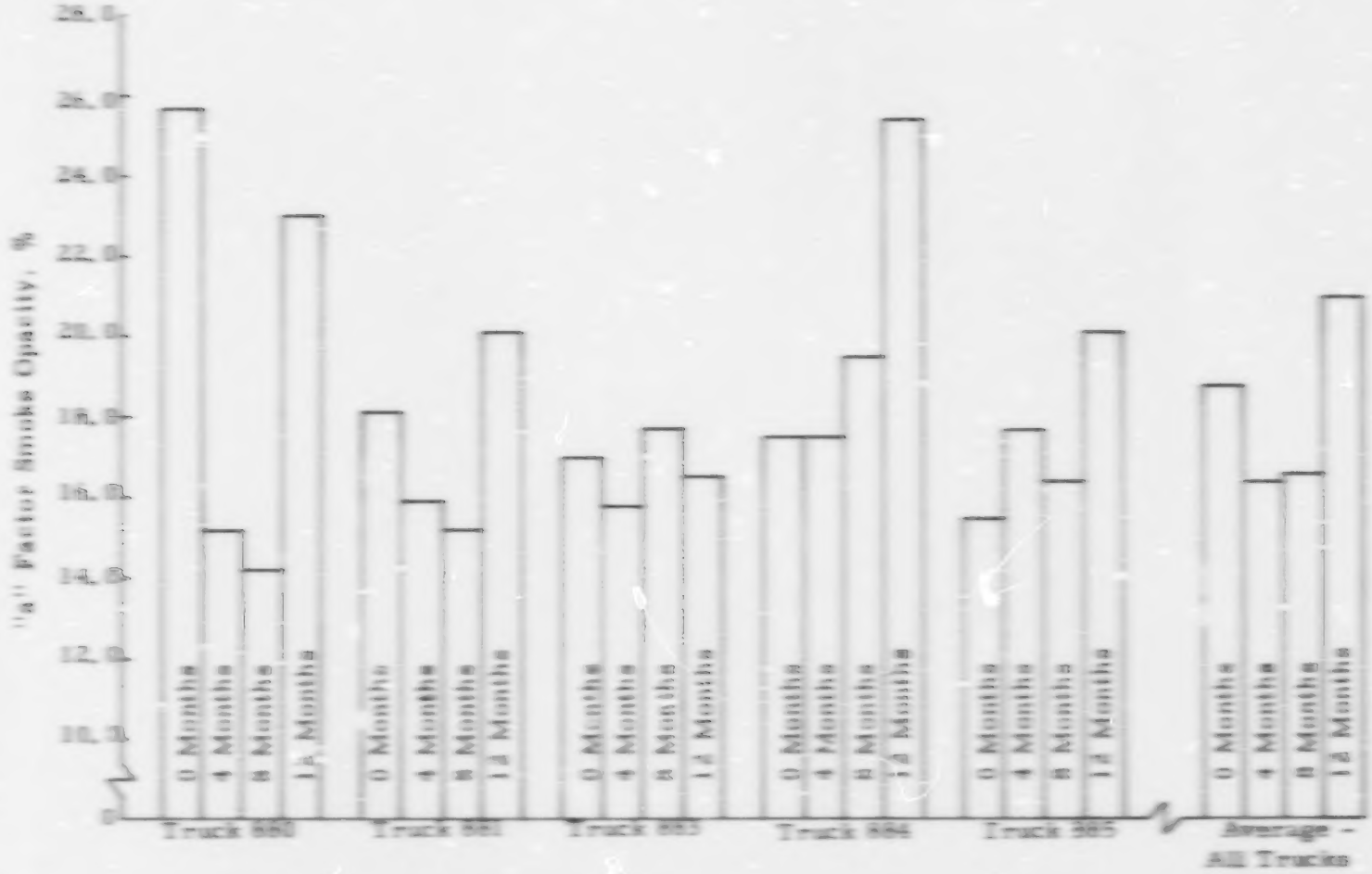


FIGURE 24. FEDERAL "a" FACTORS FOR FIVE CATERPILLAR 1150 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

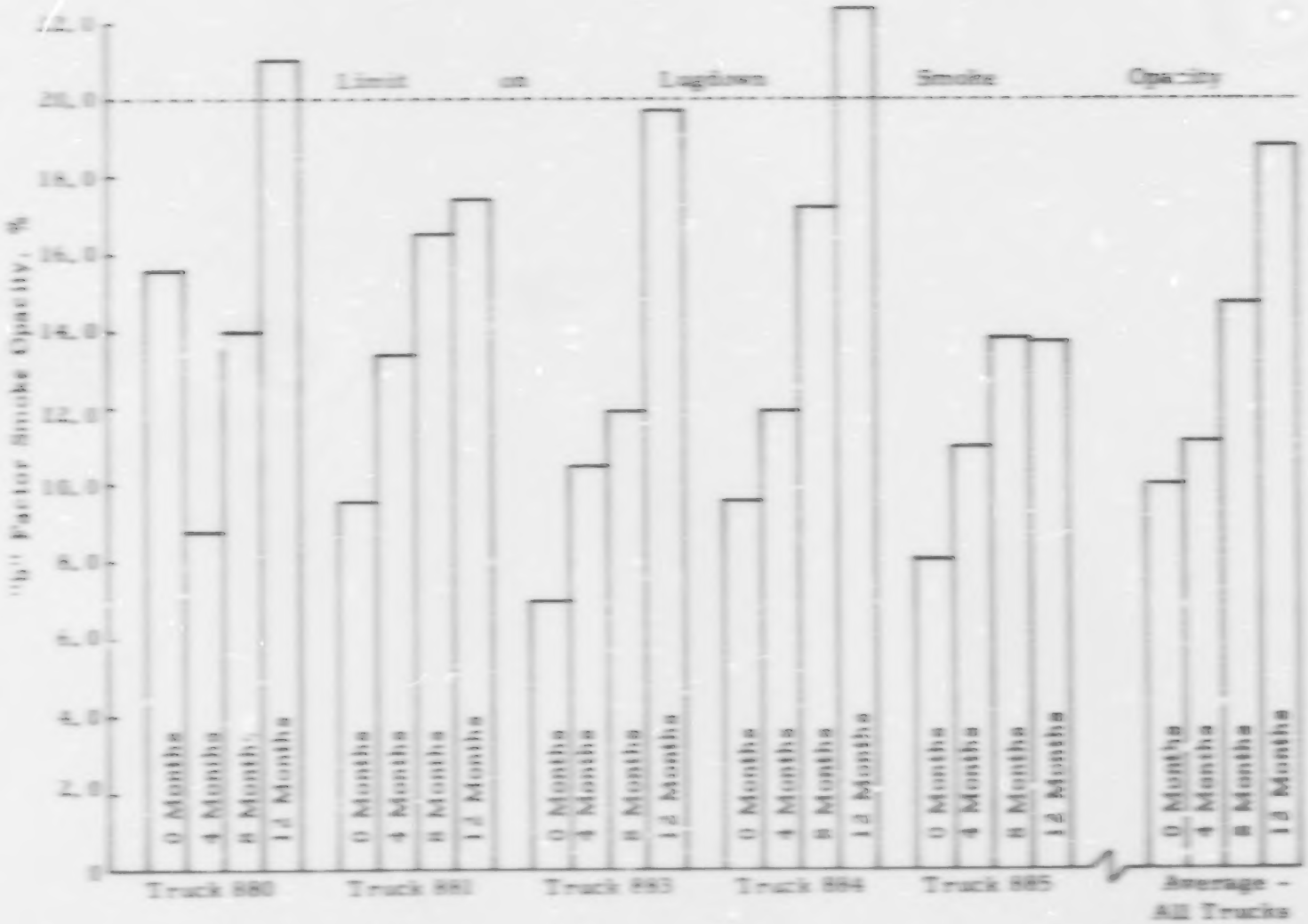


FIGURE 36. FEDERAL "b" FACTORS FOR FIVE CATERPILLAR 1150 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

Another general increase in opacity occurred between the third- and fourth-round inspections. Average fourth-round "a" and "b" values were 21.0- and 18.8-percent opacity, respectively. Hence, in the one-year test period the average "a" Factor increased very little, while the average "b" Factor almost doubled. Fourth-round "a" Factors ranged from 16.6 to 25.4 and "b" Factors from 13.7 to 22.3. Two engines had "b" Factors above the 1970 limit of 20-percent opacity. Elapsed test mileages for the year's operation were 9,200 to 19,300, and total vehicle mileage at the last test ranged from 16,900 to 27,000 miles.

3. GM DH-478 Engine/

First-round smoke opacity for these engines was low, with "a" Factors from 5.1- to 8.9-percent opacity and "b" Factors from 6.5- to 11.6-percent opacity. The respective averages were 7.3 and 9.2. All of the smoke factors are shown in Figures 31 and 32. Initial vehicle mileage was 760 to 7,100 miles.

An opacity increase for all four engines was registered at the second inspection. The average "a" and "b" values remained low, however, just 11- and 13-percent opacity, respectively. Another, somewhat larger, increase was generally noted at the third-round test. In particular, the engine in Truck No. 137 had smoke factors approximately five times higher than at baseline. Some component of the injection system was obviously out of adjustment. In any case, three of these engines had "b" Factors at or above 20-percent opacity. Average third-round "a" and "b" values were 16.7 and 22.4, respectively.

Fourth-round smoke factors were lower than at the third inspection, but still substantially over the corresponding baseline values. The "a" Factors at the last inspection ranged from 8.6- to 24.0-percent opacity, and averaged 14.1, while "b" Factors ranged from 12.1 to 28.5, with an average of 18.8. These averages were about twice those of the initial test. The engine in Truck No. 190 received an injection pump adjustment prior to the fourth-round test; however, the maladjusted engine in Truck No. 137, for some inexplicable reason, received no attention. After one year of operation, these vehicles had accumulated 7,000 to 10,900 test miles, and total vehicle mileage at the last inspection was 7,700 to 18,000 miles.

4. Detroit Diesel 6V-33N Engines

At their initial test, these engines generally had the low smoke factors of the other two-cycle engines in the project. First-round "a" Factors were 5.1- to 15.2-percent opacity (this latter value was far above the others) and "b" Factors ranged from 1.3- to 7.6-percent opacity. The average "a" and "b" values were 9.1 and 3.5, respectively. Figures 33 and 34 illustrate all smoke factors for the four tests. Initial vehicle mileage was 300 to 5,200 miles.

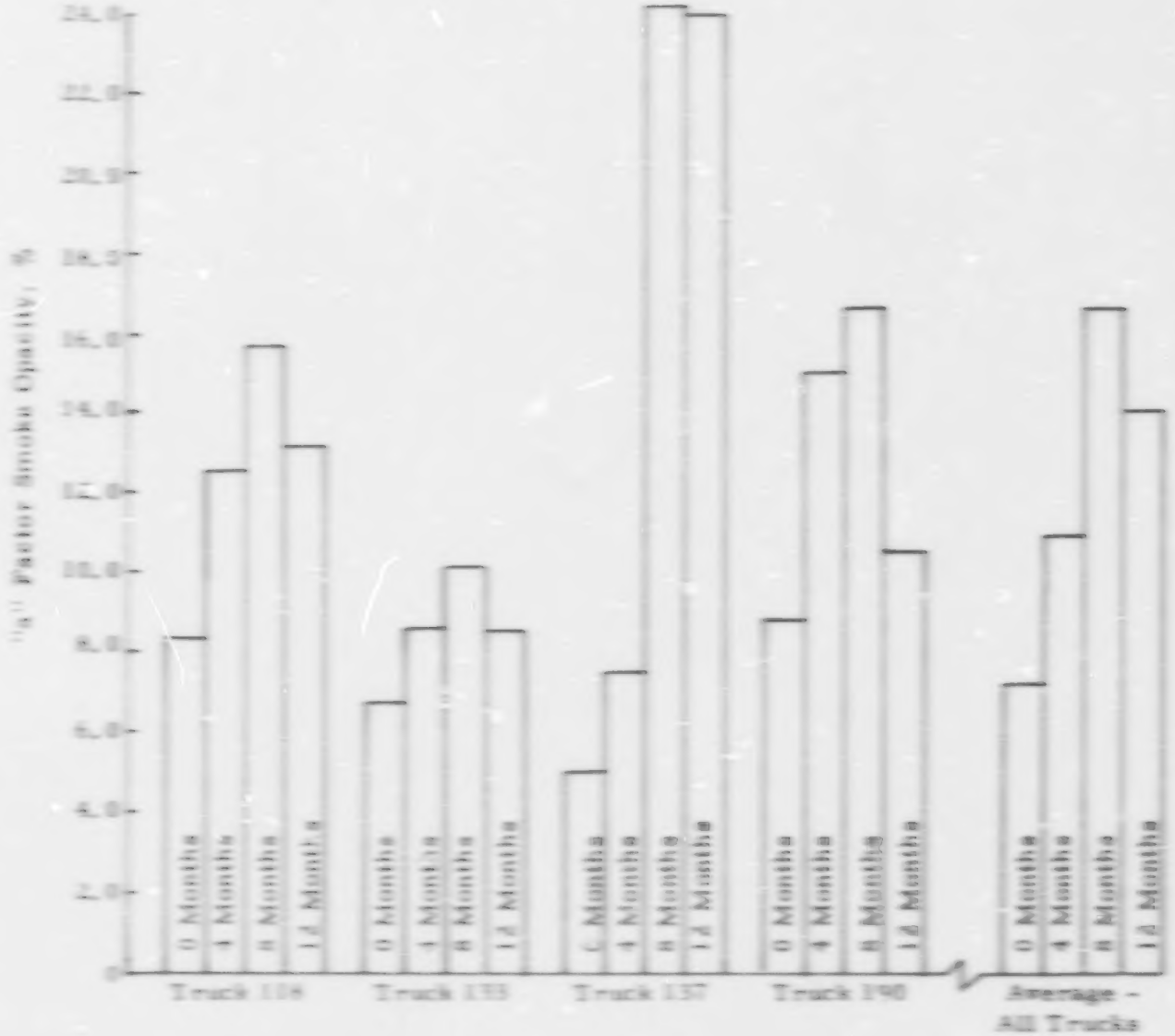


FIGURE 34. FEDERAL "a" FACTORS FOR FOUR GM DS-478 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

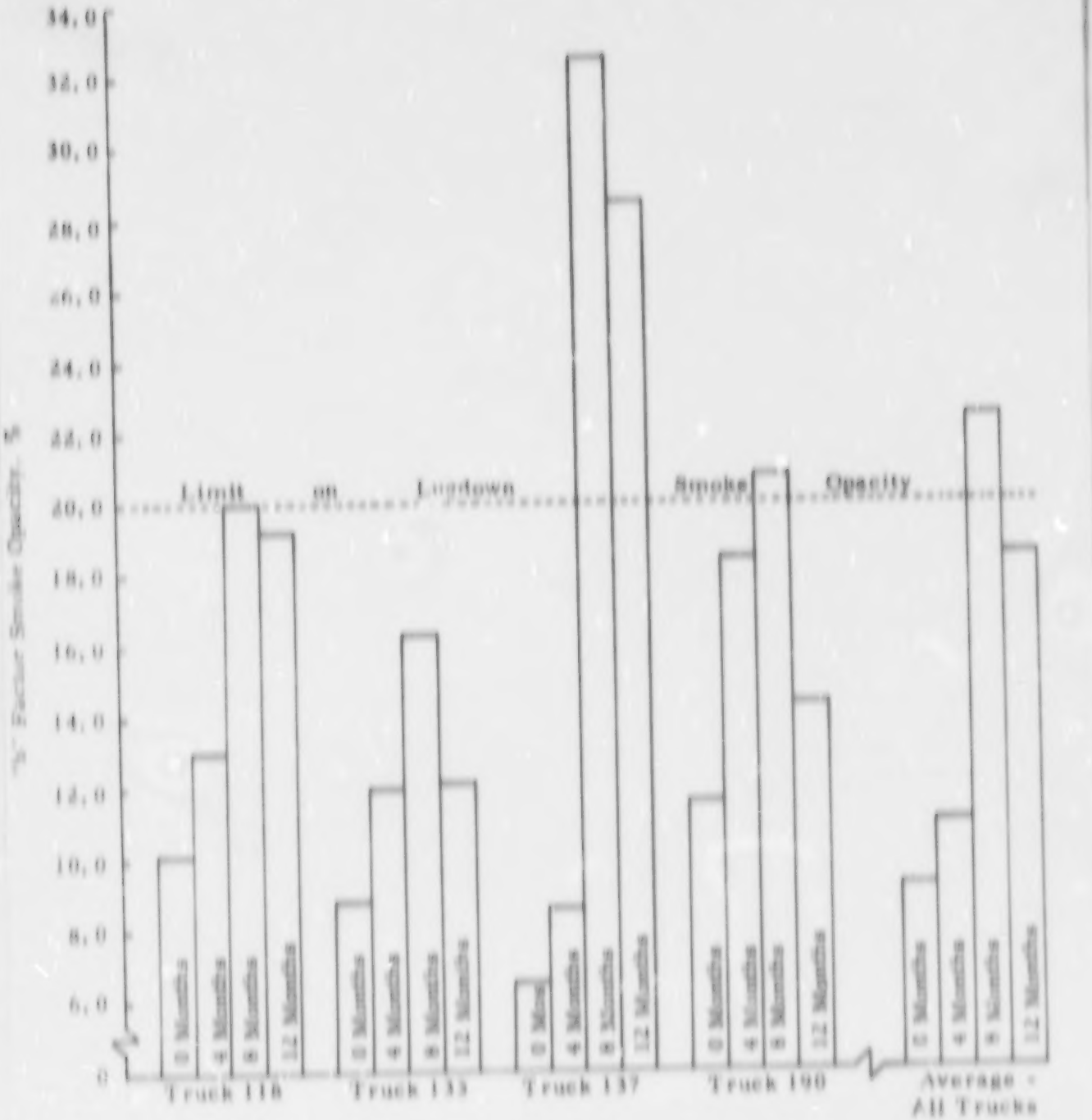


FIGURE 12. FEDERAL "b" FACTORS FOR FOUR GM DH-478 ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

FIGURE 33. FEDERAL "a" FACTORS FOR FIVE DIESEL FUELS AT 0, 4, 8 AND 12 MONTHS

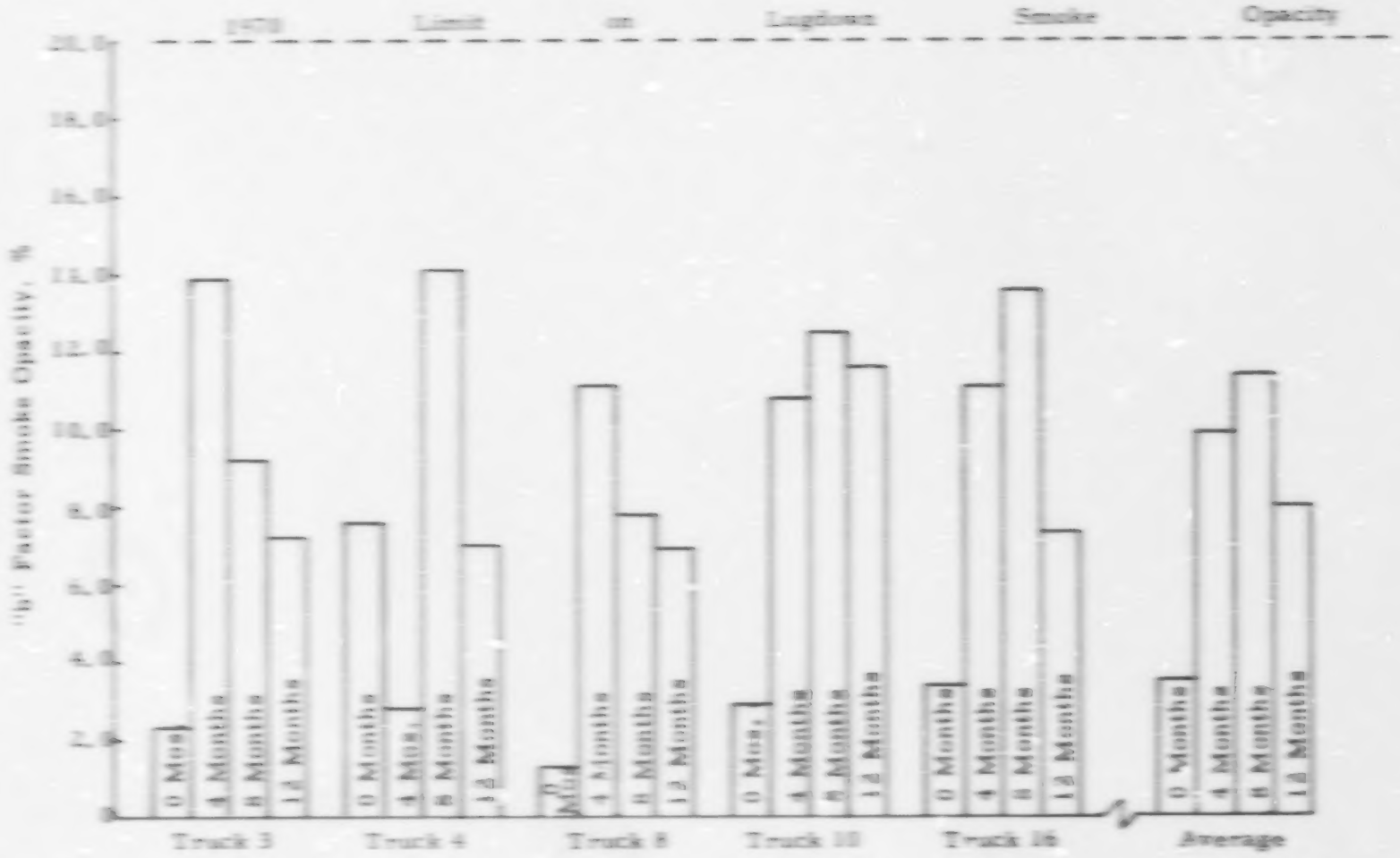


FIGURE 34. FEDERAL "b" FACTORS FOR FIVE DETROIT DIESEL 6V-53N ENGINES TESTED AT 0, 4, 8, AND 12 MONTHS

Surprising opacity changes were noted at the second-round inspection of these engines. Four engines had very large increases over their baseline opacities, while the engine (in Truck No. 4) that had high smoke at the first test showed greatly reduced opacity at the second test. This reduction was due to an adjustment of injector and valve settings, performed in response to a driver complaint of low power. The observed increases in smoke opacity are more difficult to explain. All five of the vehicles involved accumulated substantial mileage between the first and second inspections, and most of the mileage was in very hard intracity service. However, it seems unlikely that mileage alone could account for these large opacity increases. In any case, the engines performed very well, and there appeared to be no noticeable engine deterioration. The average second-round "a" and "b" Factors were 21.4- and 9.9-percent opacity, respectively, which are about 2.5-times the corresponding baseline averages.

The average third-round "a" and "b" Factors were 22.3- and 11.4-percent opacity, respectively, and hence were very close to the averages at the second test. However, even though there were only small changes on the average, there was a large increase and decrease in smoke opacity by two engines, and each change tended to cancel out the other.

Smoke opacity at the fourth inspection was generally lower than at the third test, although still considerably higher than at baseline. "a" Factors ranged from 14.7 to 18.1, with an average of 16.2, and "b" Factors were 6.9 to 11.6 and averaged 8.0. The fleet owner reported that no engine maintenance was performed between the third- and fourth-round tests; however, some uncertainty exists on this point due to the sketchiness of these records. Elapsed test mileage at the last test was 46,100 to 56,100 miles, and total vehicle mileage was 46,500 to 60,100.

5. International Harvester DV 550B Engine

First-round "a" and "b" Factors (Figure 35) were 15.9- and 17.9-percent opacity, respectively, and initial vehicle mileage was 10,000 miles. A slight increase over this baseline opacity was registered at the second test, and a much greater increase noted at the third inspection. At that time the "b" Factor was over 20-percent opacity. Fourth-round "a" and "b" values were 22.4 and 30.3, respectively. Elapsed test mileage was 20,500 and total vehicle mileage was 30,500. No engine maintenance that directly affected smoke output was performed during the one-year test period.

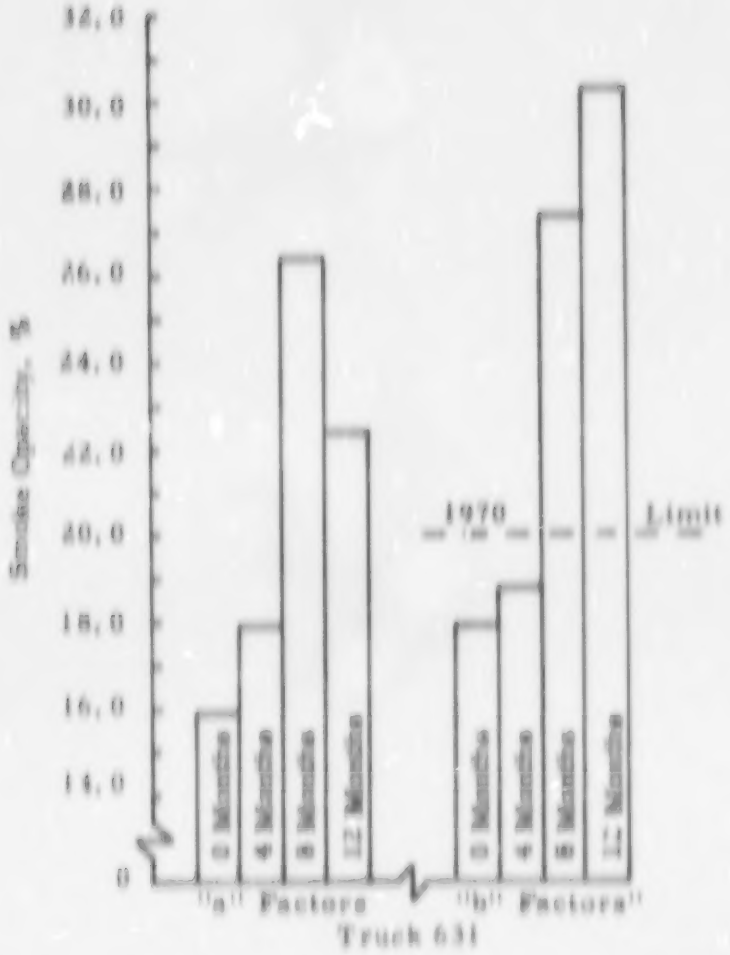


FIGURE 45. FEDERAL "a" AND "b" FACTORS
FOR AN IHC DV 550B ENGINE TESTED
AT 0, 4, 8, AND 12 MONTHS

V. STATISTICAL ANALYSIS OF SMOKE TEST DATA

In addition to the brief statistical analysis performed on the various groups of data in the previous section, the smoke test results have been further analyzed in two ways. First, "a" and "b" Factors for the entire fleet were analyzed on a test-by-test basis. This analysis was straightforward, but thorough; the statistical quantities obtained were the range, mean value, standard deviation, coefficient of variation and the first, second, and third quartiles. The relative frequency distribution and relative cumulative frequency distribution of the "a" and "b" Factors for each test were also obtained and are presented in both tabular and graphical form. Since the primary objective of this project was to determine how the smoke output from these engines changed during the one-year test period, it is particularly informative to compare the analysis for each test round. The statistical quantities included in the tables of the previous section may be referred to in order to determine how the data for a particular group of engines changed over the test period. Second, the average "a" and "b" Factors of several groups of engines were compared to similar averages for the entire test fleet. The comparison thus obtained illustrates the relationship between time and mileage and the observed changes in smoke opacity for the entire fleet and some of its component groups.

A. Analysis of First-Round Data

The pertinent statistical data for the first-round "a" and "b" Factors are presented in Table 10. Figures 36 and 37 illustrate, respectively, the relative frequency distribution and the relative cumulative frequency distribution of the "a" Factors. The relative frequency distribution (Figure 36) is moderately biased to the left, or lower, end of the opacity scale, with its peak occurring in the 4- to 8-percent opacity interval. This peak is caused by the low "a" Factors of the ten 6V-71N and six 8V-71N two-cycle engines. The interval from 8- to 12-percent opacity contains test results of several types of engines, mainly the Cummins NH-250, GM DH-478, and Detroit Diesel 6V-53N. The interval from 12- to 20-percent opacity contains most of the "a" Factors from the turbocharged Mack ENDT 675 and ENDT 675B engines and the midrange Caterpillar 1145 and 1150 engines. The small peak in the interval from 24- to 28-percent opacity is the result of the "a" Factors of several other turbocharged engines. No engine produced an "a" Factor that exceeded the 1970 limit of 40-percent opacity.

The relative cumulative frequency distribution (Figure 37) shows the percentage of all "a" Factors less than a given opacity level. For instance, about 63 percent of the "a" Factors are equal to or less than 12-percent opacity. (Conversely, 37 percent of all "a" Factors is equal to or greater than 12-percent opacity.) The curve has its greatest slope (or rate of change) from 4- to 8-percent opacity, indicative of the large number of factors in this interval. The curve has its least slope in the intervals about 20-percent opacity, which corresponds to the small number of "a" Factors in these

TABLE 10. STATISTICAL ANALYSIS OF FIRST-ROUND "a" AND "b" FACTORS FOR ALL FLEET ENGINES

"a" Factors

Percent Opacity Interval	Frequency	Frequency Percentage	Cumulative Percentage
0 to 3.99	6	8.6	8.6
4 to 7.99	24	34.3	42.9
8 to 11.99	14	20.0	62.9
12 to 15.99	10	14.3	77.2
16 to 19.99	10	14.3	91.5
20 to 23.99	1	1.4	92.9
24 to 27.99	4	5.7	98.6
28 to 31.99	1	1.4	100.0

Range:	1.5 to 28.7
Total Range:	27.2
Mean:	10.9
Standard Deviation:	6.5
Coefficient of Variation:	0.60
First Quartile:	6.0
Second Quartile:	8.7
Third Quartile:	15.6

"b" Factors

Percent Opacity Interval	Frequency	Frequency Percentage	Cumulative Percentage
1 to 2.99	9	12.8	12.8
3 to 4.99	14	20.0	32.8
5 to 6.99	12	17.2	50.0
7 to 8.99	10	14.3	64.3
9 to 10.99	9	12.8	77.1
11 to 12.99	5	7.1	84.2
13 to 14.99	3	4.3	88.5
15 to 16.99	4	5.7	94.2
17 to 18.99	3	4.3	98.6
19 to 20.99	0	0	98.6
21 to 22.99	1	1.4	100.0

Range:	1.0 to 22.4
Total Range:	21.4
Mean:	7.9
Standard Deviation:	4.8
Coefficient of Variation:	0.61
First Quartile:	4.1
Second Quartile:	6.9
Third Quartile:	10.9

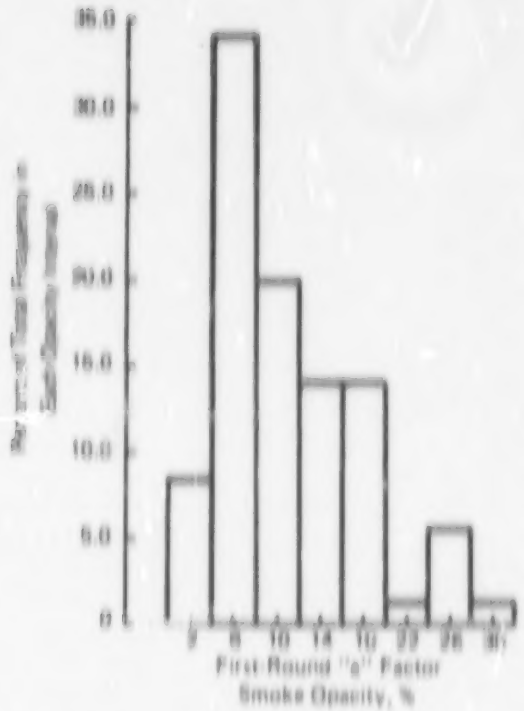


FIGURE 36. RELATIVE FREQUENCY DISTRIBUTION OF FEDERAL "a" FACTORS AT FIRST-ROUND TEST

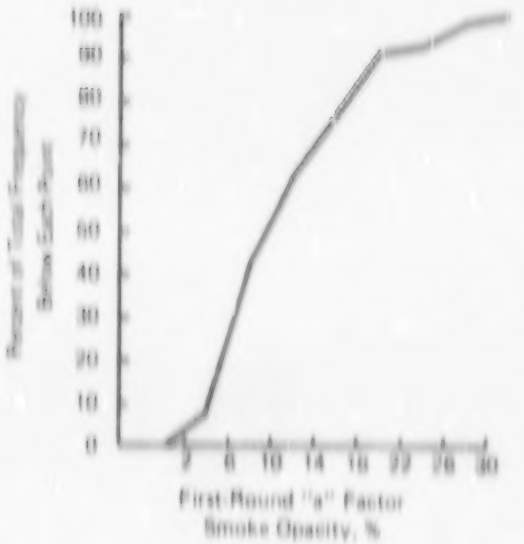


FIGURE 37. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF FEDERAL "a" FACTORS AT FIRST-ROUND TEST

intervals. The ordinate point representing 50 percent of the total frequency corresponds to the point 8.7-percent opacity on the abscissa, which is the median value (or second quartile) of the first-round "a" Factors. The first and third quartiles are 6.0- and 15.6-percent opacity, respectively. The three quartiles divide the data into four equal parts.

The range of the first-round "a" Factors is 1.5- to 58.7-percent opacity, while the mean value is 10.9. The rather large standard deviation of 6.5 indicates a high degree of absolute variation of the data. Some 74 percent of all "a" Factors lie in the range 10.9 ± 6.5 (i.e., one standard deviation either side of the mean), or 4.4- to 17.4-percent opacity. The coefficient of variation has the value 0.60. Of course, a large variation in the data is not unexpected from a group of engines that show such widely different smoke characteristics.

Figures 38 and 39 are the relative frequency distribution and the relative cumulative frequency distributions, respectively, for the first-round "b" Factors. The relative frequency distribution is biased to the low end of the opacity scale, as in the case of the "a" Factors, but the distribution is more uniform for the "b" Factors. This can be seen by comparing Figures 36 and 38. The greatest number of "b" Factors lie in the interval from 3- to 5-percent opacity, due to the low lugdown smoke of the Detroit Diesel 6V-71N, 8V-71N, and 6V-53N engines, and the turbocharged Cummins NTC-335 engines. Several of these engines also have "b" Factors in the 1- to 3-percent opacity interval. The "b" Factors for the Cummins NH-250 engines populate the intervals from 11- to 17-percent opacity, while those of the turbocharged Mack engines and the midrange four-cycle engines lie principally in the intervals from 7- to 11-percent opacity. One "b" Factor was over the 20-percent opacity limit at the initial inspection.

The "b" Factors have a median (second quartile) value of 6.9, and first and third quartiles of 4.1 and 10.9, respectively. The range of the first-round "b" Factors is 1.0- to 22.4-percent opacity, and the mean value is 7.9. The standard deviation is 4.8, which shows the large absolute variation of the data about the mean. About 73 percent of the "b" Factors lie in the range 7.7 ± 4.8, or 2.9- to 12.5-percent opacity. The coefficient of variation is 0.64, and, when compared to the value of 0.60 for the "a" Factors, shows that the "b" Factors have the greater degree of relative variation. However, the "a" Factors have the most absolute variation.

B. Analysis of Second-Round Data

The results of the analysis of the second-round "a" and "b" Factors are given in Table II. The relative frequency distribution and the relative cumulative frequency distribution of the "a" Factors are shown in Figures 40 and 41, respectively. The relative frequency distribution is similar to that of the first-round "a" Factors. This similarity can be seen by comparing Figures 40 and 36. The second-round "a" Factors lie primarily in

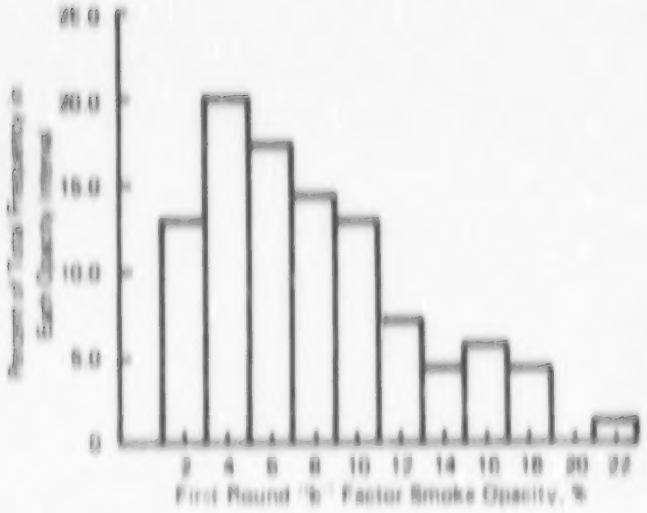


FIGURE 38. RELATIVE FREQUENCY DISTRIBUTION OF FEDERAL "b" FACTORS AT FIRST-ROUND TEST

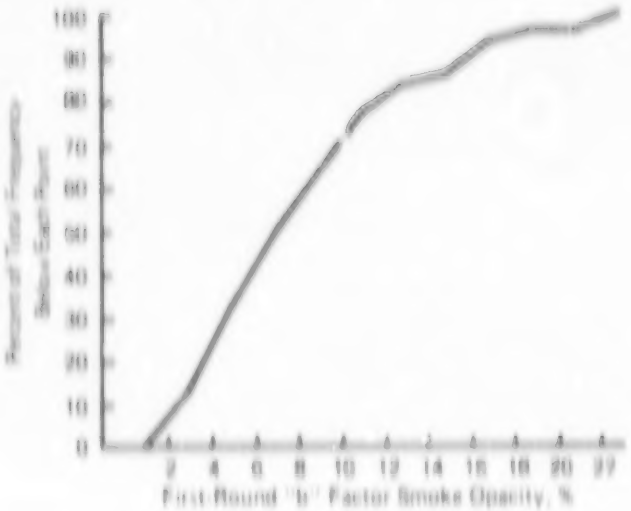


FIGURE 39. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF FEDERAL "b" FACTORS AT FIRST-ROUND TEST

TABLE II. STATISTICAL ANALYSIS OF SECOND-ROUND "a" AND "b" FACTORS FOR ALL FLEET ENGINES

"a" Factors

Percent Opacity Interval	Frequency	Frequency Percentage	Cumulative Percentage
0 to 3.99	8	11.4	11.4
4 to 7.99	17	24.3	35.7
8 to 11.99	8	11.4	47.1
12 to 15.99	14	20.0	67.1
16 to 19.99	10	14.3	81.4
20 to 23.99	5	7.2	88.6
24 to 27.99	2	2.9	91.5
28 to 31.99	3	4.3	95.8
32 to 35.99	1	1.4	97.2
36 to 39.99	1	1.4	98.6
40 to 43.99	1	1.4	100.0

Range:	1.7 to 42.2
Total Range:	40.5
Mean:	13.6
Standard Deviation:	8.8
Coefficient of Variation:	0.64
First Quartile:	6.6
Second Quartile:	12.7
Third Quartile:	18.0

"b" Factors

Percent Opacity Interval	Frequency	Frequency Percentage	Cumulative Percentage
1 to 2.99	10	14.3	14.3
3 to 4.99	5	7.2	21.5
5 to 6.99	4	5.8	27.3
7 to 8.99	12	17.2	44.5
9 to 10.99	8	11.4	55.9
11 to 12.99	10	14.3	70.2
13 to 14.99	8	11.4	81.6
15 to 16.99	1	1.4	83.0
17 to 18.99	8	11.4	94.4
19 to 20.99	1	1.4	95.8
21 to 22.99	1	1.4	97.2
23 to 24.99	1	1.4	98.6
25 to 26.99	1	1.4	100.0

Range:	1.0 to 25.0
Total Range:	24.0
Mean:	10.1
Standard Deviation:	5.8
Coefficient of Variation:	0.57
First Quartile:	6.0
Second Quartile:	10.1
Third Quartile:	13.6

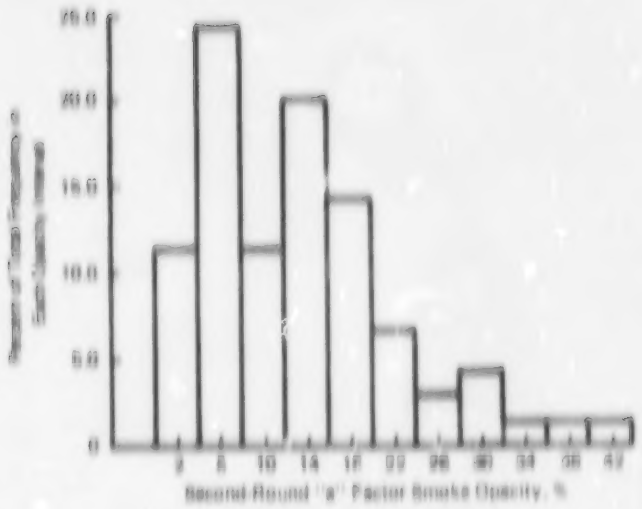


FIGURE 40. RELATIVE FREQUENCY DISTRIBUTION OF FEDERAL "a" FACTORS AT SECOND-ROUND TEST

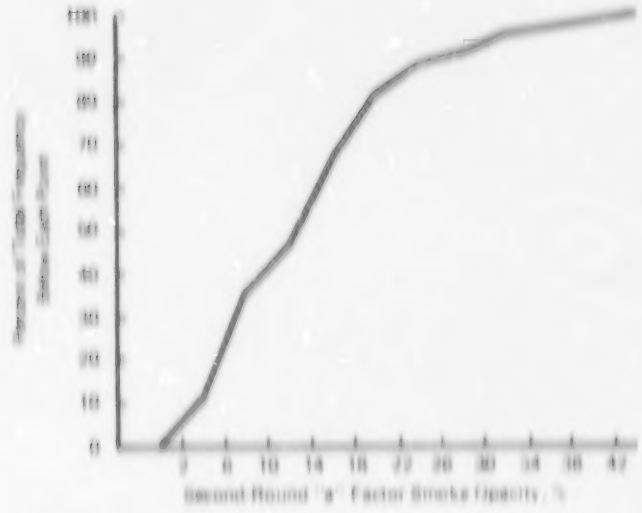


FIGURE 41. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF FEDERAL "a" FACTORS AT SECOND-ROUND TEST

the lower opacity intervals, although they are more uniformly distributed in these intervals than at the first inspection. The peak of the distribution occurs in the 4- to 8-percent opacity interval, as it did at the first inspection, and this peak again is the result of the low "a" Factors of the Detroit Diesel "71" series engines. The distribution has a smaller peak in the interval from 12- to 16-percent opacity, caused by a number of test results from Cummins NH-250 and midrange four-cycle engines. The intervals above 20-percent opacity are filled almost exclusively with "a" Factors from turbocharged engines and the Detroit Diesel 6V-53N midrange engines. Note that only one engine had a second-round "a" Factor above 40-percent opacity.

The range of the second-round "a" Factors is 1.7- to 42.2-percent opacity. The average value is 13.6, which is 2.7-percent opacity higher than for the initial data. The standard deviation is 8.8; hence, these data are also highly dispersed about the mean. Approximately 73 percent of the second-round data lie within one standard deviation either side of the mean, in the range 4.8- to 22.4-percent opacity. The coefficient of variation is 0.64, which is slightly higher than for the baseline "a" Factors.

The relative frequency distribution and the relative cumulative frequency distribution of the second-round "b" Factors are shown in Figures 42 and 43, respectively. Figure 42 shows that the bulk of the data is distributed in the intervals from 7- to 15-percent opacity. This is a definite shift up the opacity scale from the first-round distribution (compare Figures 42 and 38). The second-round distribution has its peak in the interval from 7- to 9-percent opacity, where the "b" Factors for the Detroit Diesel 6V-71N and Cummins V-903 engines are found. Two lesser peaks occur in the intervals 1- to 3-percent opacity (Detroit Diesel 8V-71N) and 11- to 13-percent opacity (turbocharged Mack engines and several midrange engines). Only four "b" Factors, representing about six percent of the second-round data, are over the 20-percent opacity limit.

The range of these "b" Factors is 1.0- to 25.0-percent opacity, which is very similar to the range of first-round data. The mean value is 10.1, or 2.2-percent opacity higher than for the baseline "b" Factors. The standard deviation (5.8) is slightly higher than that of the baseline data, and about 64 percent of the second-round "b" Factors are within one standard deviation of the mean, i.e., in the range 4.3- to 15.9-percent opacity. The second-round "b" Factors have coefficient of variation 0.57, which is slightly lower than for the first-round data.

C. Analysis of Third-Round Data

The results of the analysis of the third-round smoke factors are presented in Table 12 and Figures 44 to 47, inclusive. The relative frequency distribution of the "a" Factors (Figure 44) has its peak in the interval from 4- to 8-percent opacity, as did the frequency distributions of the first- and

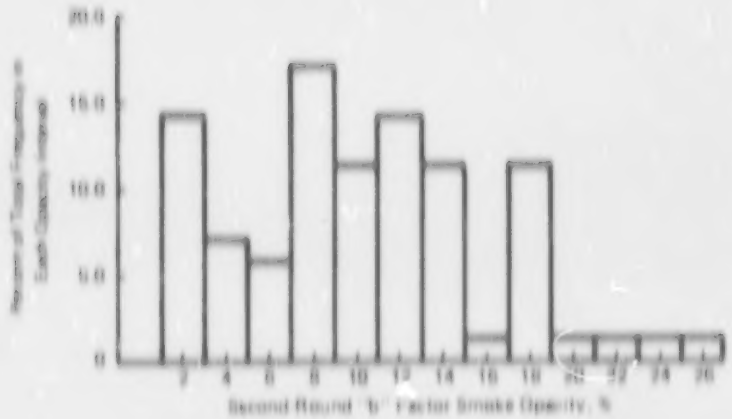


FIGURE 42. RELATIVE FREQUENCY DISTRIBUTION OF FEDERAL "b" FACTORS AT SECOND-ROUND TEST

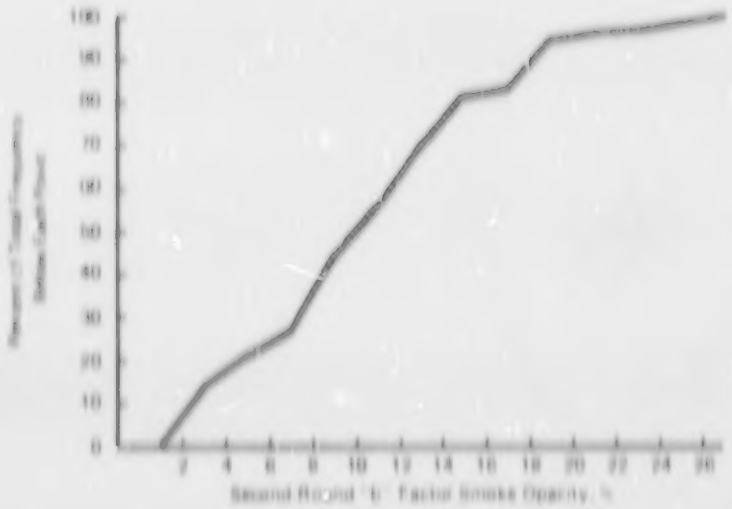


FIGURE 43. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF FEDERAL "b" FACTORS AT SECOND-ROUND TEST

TABLE 12. STATISTICAL ANALYSIS OF THIRD-FOUND "a" AND "b" FACTORS FOR ALL FLEET ENGINES

"a" Factors

Percent Opacity Interval	Frequency	Frequency Percentage	Cumulative Percentage
0 to 3.99	3	3.1	4.1
4 to 7.99	13	18.9	25.2
8 to 11.99	12	17.8	43.0
12 to 15.99	10	14.5	58.1
16 to 19.99	11	15.9	74.0
20 to 23.99	7	10.1	84.1
24 to 27.99	5	7.2	91.4
28 to 31.99	4	5.8	97.2
32 to 35.99	1	1.4	98.6
36 to 39.99	1	1.4	97.1
40 to 43.99	1	1.4	98.6
44 to 47.99	1	1.4	100.0

Range:	1.5 to 44.0
Total Range:	42.5
Mean:	16.0
Standard Deviation:	9.4
Coefficient of Variation:	0.59
First Quartile:	8.2
Second Quartile:	14.7
Third Quartile:	20.6

"b" Factors

Percent Opacity Interval	Frequency	Frequency Percentage	Cumulative Percentage
0 to 1.99	2	2.9	2.9
2 to 3.99	5	7.2	10.1
4 to 5.99	7	10.1	20.3
6 to 7.99	12	17.4	37.7
8 to 9.99	5	7.2	44.9
10 to 11.99	3	4.3	49.2
12 to 13.99	7	10.1	59.4
14 to 15.99	6	8.7	68.1
16 to 17.99	6	8.7	76.8
18 to 19.99	6	8.7	85.5
20 to 21.99	2	2.9	88.4
22 to 23.99	2	2.9	91.3
24 to 25.99	2	2.9	94.2
26 to 27.99	2	2.9	97.1
28 to 29.99	1	1.4	98.6
30 to 31.99	0	0	98.6
32 to 33.99	1	1.4	100.0

Range:	0.5 to 32.5
Total Range:	32.1
Mean:	12.5
Standard Deviation:	7.4
Coefficient of Variation:	0.59
First Quartile:	6.8
Second Quartile:	12.5
Third Quartile:	17.5

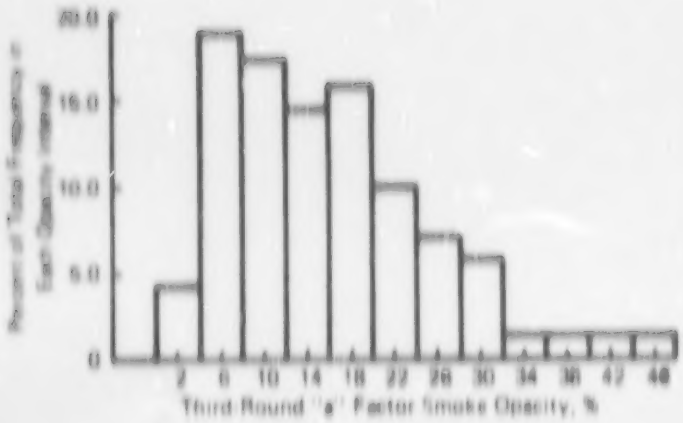


FIGURE 44. RELATIVE FREQUENCY DISTRIBUTION OF FEDERAL "a" FACTORS AT THIRD-ROUND TEST

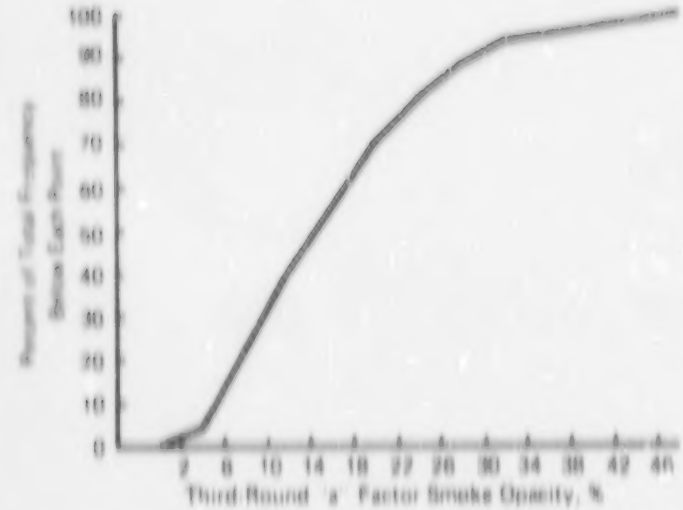


FIGURE 45. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF FEDERAL "a" FACTORS AT THIRD-ROUND TEST

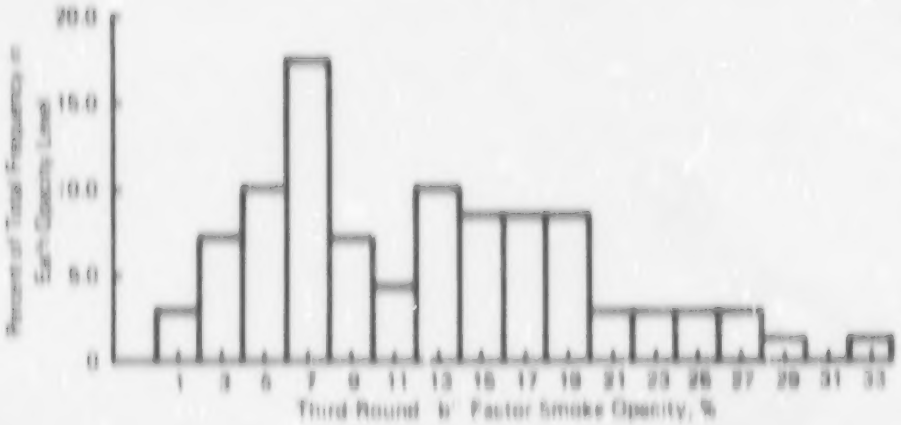


FIGURE 46. RELATIVE FREQUENCY DISTRIBUTION OF FEDERAL "b" FACTORS AT THIRD-ROUND TEST

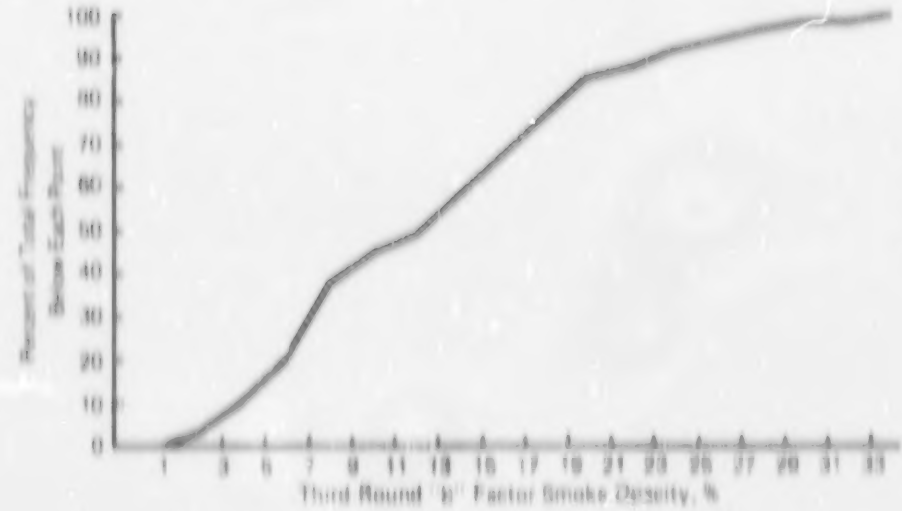


FIGURE 47. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF FEDERAL "b" FACTORS AT THIRD-ROUND TEST

second-round "a" Factors. However, the third-round data are more evenly distributed in the middle of the opacity range. The "a" Factors for the "71" series two-cycle engines again occupy the lower intervals, up to 12-percent opacity. The intervals extending from 12- to 20-percent opacity contain the data for most of the Cummins NH-250 and Caterpillar 1150 engines. The intervals from 20- to 28-percent opacity are populated with "a" Factors of the Caterpillar 1145 engines, some of the lower smoke-producing turbocharged engines, and the two-cycle "53" series engines. The intervals above 28-percent opacity contain data from the remaining turbocharged engines. Two "a" Factors are over the 40-percent opacity limit.

The third-round "a" Factors range from 1.5- to 44.0-percent opacity and have a mean value of 16.0, which is a 2.4-percent opacity increase over the second-round average. The absolute and relative variations of the third-round data remain high, as evidenced by the large values of the standard deviation and coefficient of variation, respectively. About 70 percent of the data lie in the range 6.6- to 25.4-percent opacity, or within one standard deviation either side of the mean.

The relative frequency distribution of the third-round "b" Factors (Figure 46) shows that the bulk of the data are contained in the intervals from 2- to 10-percent opacity (mostly two-cycle "71" engines and turbocharged Cummins NTC-335 engines) and in the intervals from 12- to 20-percent opacity (mostly midrange intracity engines, naturally aspirated Cummins engines, and turbocharged Mack 675 engines). The intervals about 20-percent opacity have "b" Factors from a few of the midrange engines and Cummins NH-250 engines. Nine "b" Factors, or about 14 percent of the data, are over 20-percent opacity.

The values of the third-round data cover a broad range, from 0.5- to 32.6-percent opacity. The mean value is 12.5, which is 2.4-percent opacity higher than for the second-round data. The standard deviation of these data is greater than for the first- or second-round tests; hence, there is less tendency for the data to converge as time passes and the opacity values spread out about the mean. About 67 percent of the third-round "b" Factors are within one standard deviation of the mean, or from 5.1- to 19.9-percent opacity.

D. Analysis of Fourth-Round Data

Table 13 contains the results of the analysis performed on the fourth-round data. The relative frequency distribution and relative cumulative frequency distribution of the "a" Factors are shown in Figures 48 and 49, respectively. It can be seen in Figure 48 that the peak of the frequency distribution is in the interval from 12- to 16-percent opacity, whereas at the three previous inspections the peak was in the interval from 4- to 8-percent opacity. This latter interval still contains nearly all the "a" Factors of the "71" series two-cycle engines. The data from most of the larger four-

TABLE 13. STATISTICAL ANALYSIS OF FOURTH-ROUND "a" AND "b" FACTORS FOR ALL FLEET ENGINES

"a" Factors

Percent Opacity Interval	Frequency	Frequency Percentage	Cumulative Percentage
0 to 3.99	0	0	0
4 to 7.99	11	16.2	16.2
8 to 11.99	13	19.1	35.3
12 to 15.99	14	20.6	55.9
16 to 19.99	10	14.7	70.6
20 to 23.99	8	11.8	82.4
24 to 27.99	5	7.4	89.8
28 to 31.99	5	7.4	97.2
32 to 35.99	0	0	97.2
36 to 39.99	1	1.4	98.6
40 to 43.99	0	0	98.6
44 to 47.99	1	1.4	100.0

Range:	4.8 to 44.9
Total Range:	40.1
Mean:	16.2
Standard Deviation:	8.2
Coefficient of Variation:	0.51
First Quartile:	9.8
Second Quartile:	14.4
Third Quartile:	22.3

"b" Factors

Percent Opacity Interval	Frequency	Frequency Percentage	Cumulative Percentage
0 to 1.99	0	0	0
2 to 3.99	7	10.3	10.3
4 to 5.99	8	11.8	22.1
6 to 7.99	10	14.7	36.8
8 to 9.99	2	2.9	39.7
10 to 11.99	6	8.8	48.5
12 to 13.99	10	14.7	63.2
14 to 15.99	2	2.9	66.1
16 to 17.99	3	4.4	70.5
18 to 19.99	8	11.8	82.3
20 to 21.99	3	4.4	86.7
22 to 23.99	4	5.9	92.6
24 to 25.99	0	0	92.6
26 to 27.99	0	0	92.6
28 to 29.99	1	1.5	94.1
30 to 31.99	3	4.4	98.5
32 to 33.99	1	1.5	100.0

Range:	2.0 to 33.4
Total Range:	31.4
Mean:	14.0
Standard Deviation:	7.9
Coefficient of Variation:	0.61
First Quartile:	6.3
Second Quartile:	12.0
Third Quartile:	19.2

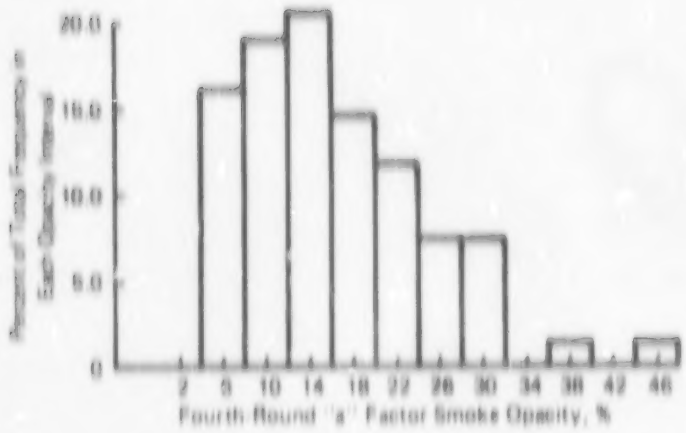


FIGURE 48. RELATIVE FREQUENCY DISTRIBUTION OF FEDERAL "a" FACTORS AT FOURTH-ROUND TEST

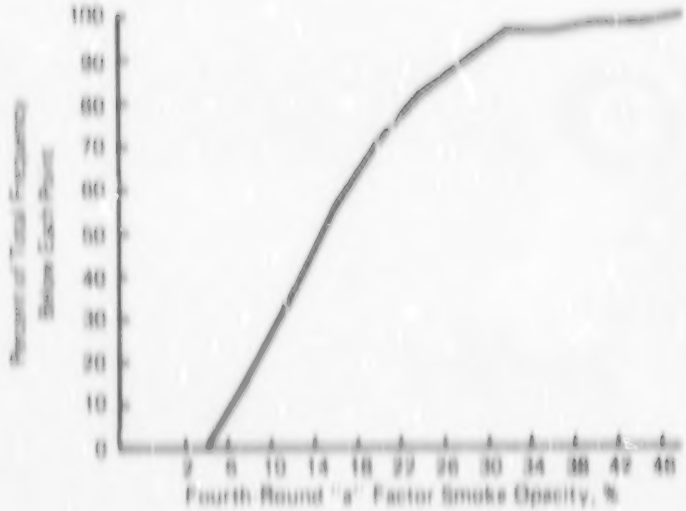


FIGURE 49. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF FEDERAL "a" FACTORS AT FOURTH-ROUND TEST

cycle naturally aspirated engines are in the intervals from 8- to 20-percent opacity, along with "a" Factors from the two-cycle "53" engines. However, many of the data for the smaller, midrange four-cycle engines are in the intervals from 18- to 28-percent opacity. Above 28-percent opacity are the "a" Factors from the turbocharged Mack 675 engines. One "a" Factor is over the 40-percent opacity limit.

The range of the "a" Factors is 4.8- to 44.9-percent opacity (excepting the "a" Factor for Bus No. 817--see Section IV, Part A), and the mean value is 16.2, almost unchanged from the third-round average and 5.5-percent opacity over the baseline average. The standard deviation and coefficient of variation of the fourth-round data is 8.2 and 0.51, respectively, and both of these quantities are slightly lower than for the third-round data. About 68 percent of the "a" Factors are in the range 8.0- to 24.4-percent opacity, or within one standard deviation either side of the mean.

The relative frequency distribution and relative cumulative frequency distribution of the fourth-round "b" Factors are illustrated in Figures 50 and 51, respectively. Figure 50 shows the irregular distribution of the data. There are two distinct peaks in this distribution, one in the interval from 6- to 8-percent opacity (Cummins NTC-335, and the 6V-53 and 6V-71 engines) and another in the interval from 12- to 14-percent opacity (Cummins V-903 and turbocharged Mack engines). The intervals from 16- to 24-percent opacity contain data for the Cummins NH-250 and midrange four-cycle engines. The lowest intervals, from 2- to 6-percent opacity, contain "b" Factors from the 8V-71 engines. Twelve "b" Factors are above the 20-percent opacity limit.

The "b" Factors range from 2.0- to 44.4-percent opacity. The mean value is 13.0, which is 0.5-percent opacity over the third-round average and 5.1 over the average at baseline. The standard deviation is 7.9, the largest such deviation for the four sets of "b" Factor data. Some 68 percent of the data is between 5.1- and 20.9-percent opacity, or within one standard deviation either side of the mean.

E. Analysis For Various Engine Groups

The average "a" and "b" Factors for various groups of engines at each of the four inspections are presented in Table 14. This information shows how elapsed time and mileage affect the smoke output of two-cycle and four-cycle engines, naturally aspirated and turbocharged engines, and intracity and intercity service engines. Also given are the average smoke factors for the entire fleet at each inspection. Hence, the average opacities of these engine groups can be compared to the averages for the fleet as a whole.

The test fleet was first divided into groups of two-cycle and four-cycle engines. Each group contains engines in intracity and intercity service

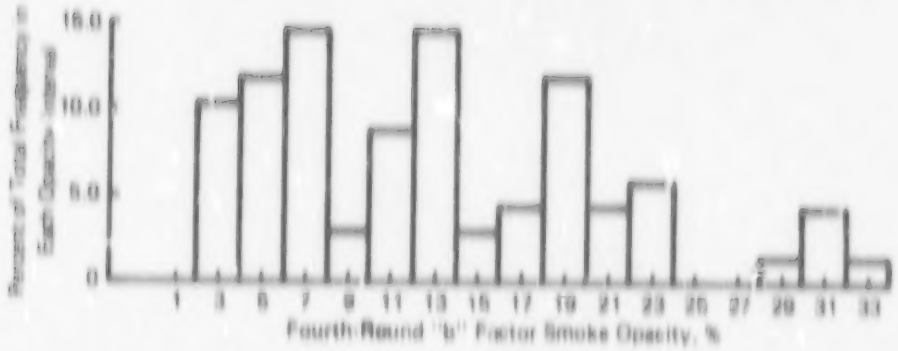


FIGURE 50. RELATIVE FREQUENCY DISTRIBUTION OF FEDERAL "b" FACTORS AT FOURTH-ROUND TEST

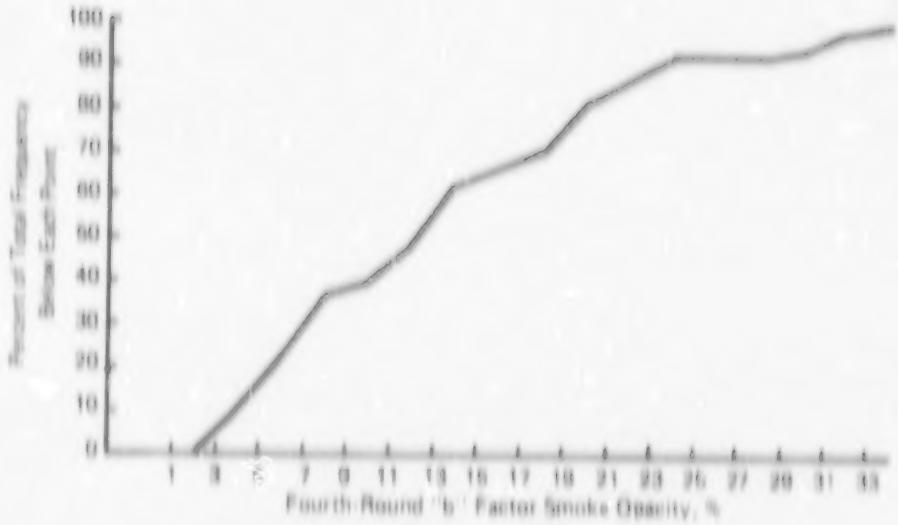


FIGURE 51. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF FEDERAL "b" FACTORS AT FOURTH-ROUND TEST

TABLE 14. AVERAGE "a" AND "b" FACTORS FOR VARIOUS ENGINE GROUPS

Test No.	Fleet		Two-Cycle Engines				Four-Cycle Engines			
	Avg. "a" Factor	Avg. "b" Factor	Avg. "a" Factor	Avg. "b" Factor	Difference*, Δ"a"	Δ"b"	Avg. "a" Factor	Avg. "b" Factor	Difference*, Δ"a"	Δ"b"
1	10.4	7.4	6.0	3.4	-4.4	-4.0	13.7	10.0	+2.8	+2.1
2	13.6	10.1	8.5	5.3	-5.1	-4.8	16.7	12.4	+3.1	+2.8
3	16.8	12.5	10.3	6.4	-5.7	-6.1	19.4	14.2	+3.4	+3.7
4	16.2	13.0	9.9	5.6	-6.3	-7.4	19.9	17.3	+3.7	+4.3

	N. A. Engines				T. C. Engines			
	Avg. "a" Factor	Avg. "b" Factor	Difference*, Δ"a"	Δ"b"	Avg. "a" Factor	Avg. "b" Factor	Difference*, Δ"a"	Δ"b"
1	9.5	8.1	-: 4	+0.2	17.1	6.1	+6.2	-1.8
2	11.3	10.3	-2.3	+0.2	23.7	9.5	+10.1	-0.6
3	13.6	12.8	-2.4	+0.3	27.4	11.0	+11.4	-1.5
4	14.3	13.4	-1.9	+0.4	25.0	10.7	+8.8	-2.3

	Intracity Engines				Intercity Engines			
	Avg. "a" Factor	Avg. "b" Factor	Difference*, Δ"a"	Δ"b"	Avg. "a" Factor	Avg. "b" Factor	Difference*, Δ"a"	Δ"b"
1	11.9	7.6	+1.0	-0.3	9.7	7.8	-1.2	-0.1
2	15.1	10.5	+1.5	+0.4	11.9	9.7	-1.7	-0.4
3	18.5	13.6	+2.5	+1.1	13.1	11.3	-2.4	-1.2
4	16.9	13.5	+0.7	+0.5	14.9	11.9	-1.3	-1.1

*From fleet average.

and, in addition, the group of four-cycle engines contains naturally aspirated and turbocharged models. Looking at Figure 52, where the data are illustrated, it can be seen that the average "a" and "b" Factors for all fleet engines increase from test to test in a highly similar manner. Almost identical opacity increases occur between the first and second, and again between the second and third, inspections. The four-cycle engines follow this general trend almost exactly, as do the two-cycle engines except at the fourth-round test where there is a slight decrease from the average third-round smoke factors. Quantitatively, the two-cycle engines have average "a" and "b" Factors 4- to 7-percent opacity below the fleet average, while the group of four-cycle engines is 2- to 4-percent opacity above the fleet average (Table 14).

The fleet was next considered as being composed of groups of naturally aspirated and turbocharged engines. The two-cycle engines are considered to be naturally aspirated, so this group contains both two- and four-cycle engines. In addition, each of the two groups has engines in intracity and intercity service. Figure 53 illustrates the changes in the average smoke factors. It is evident that the naturally aspirated engines follow the general trend of the fleet, while the turbocharged models differ from this pattern only at the last inspection, where the average opacities decrease slightly from those of the third-round test. The data in Table 14 shows that the naturally aspirated engines have average "a" and "b" Factors about 1- to 2-percent opacity below the fleet average. However, the turbocharged engines have "a" Factors some 6- to 11-percent opacity above, and "b" Factors about 1- to 2-percent opacity below, the average smoke factors of the fleet.

For the final analysis the fleet was divided into groups of engines in intracity and intercity service. Both groups contain two-cycle and four-cycle engines, as well as naturally aspirated and turbocharged models. The average smoke factors for these groups are shown in Figure 54. The intercity engines show progressively higher average smoke factors at each inspection, as do the smoke factors of the entire fleet. The intracity engines have a slight drop between the third- and fourth-round averages, as do some of the engine groups discussed previously. On a more quantitative basis, the intracity engines have average "a" and "b" Factors about 1- to 2-percent opacity higher than the fleet smoke factors, while the smoke factors for the intercity engines are 1- to 5-percent opacity under the averages for the entire fleet.

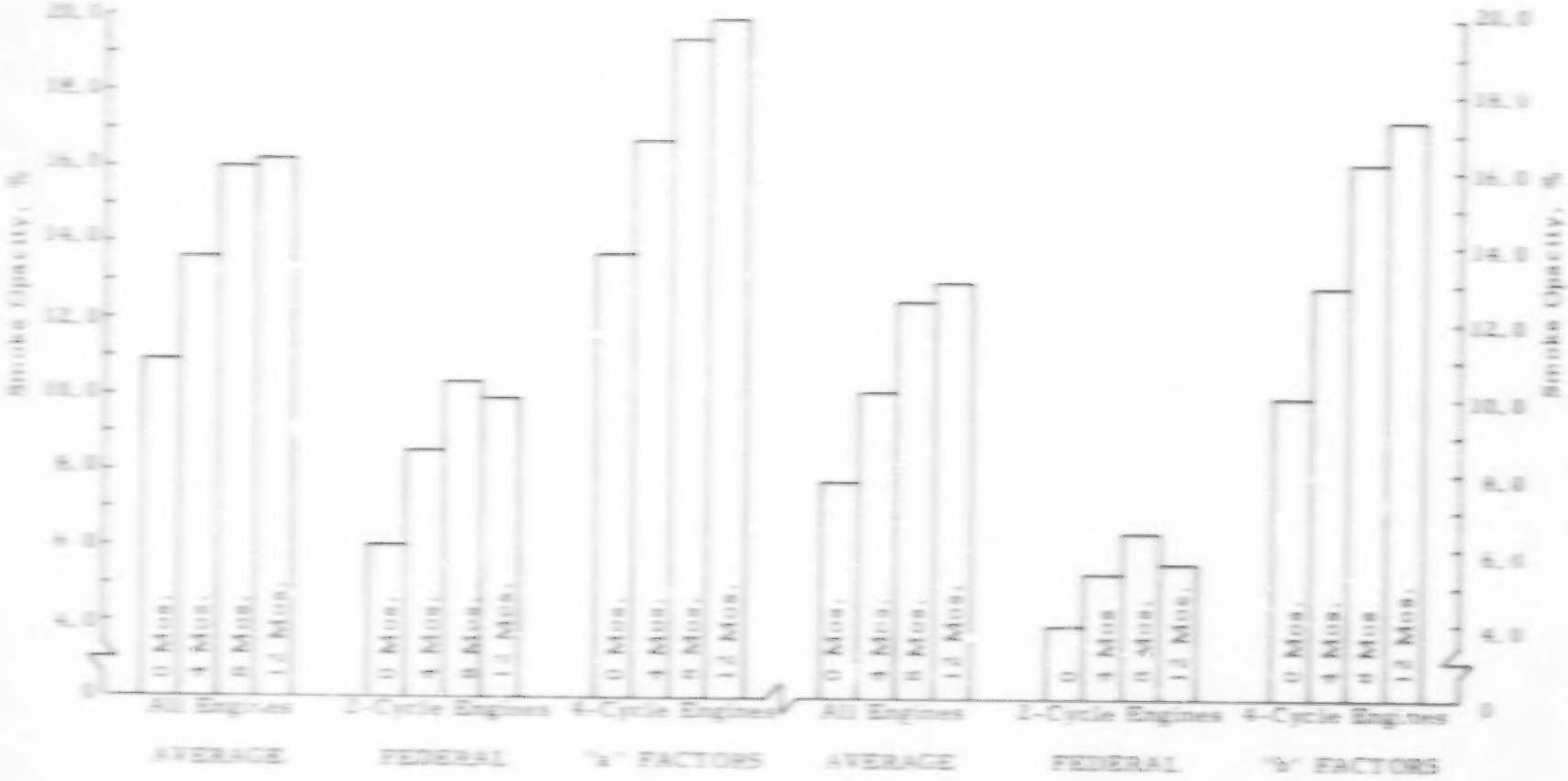


FIGURE 52. AVERAGE "a" AND "b" FACTORS FOR ALL FLEET ENGINES, TWO-CYCLE FLEET ENGINES, AND FOUR-CYCLE FLEET ENGINES

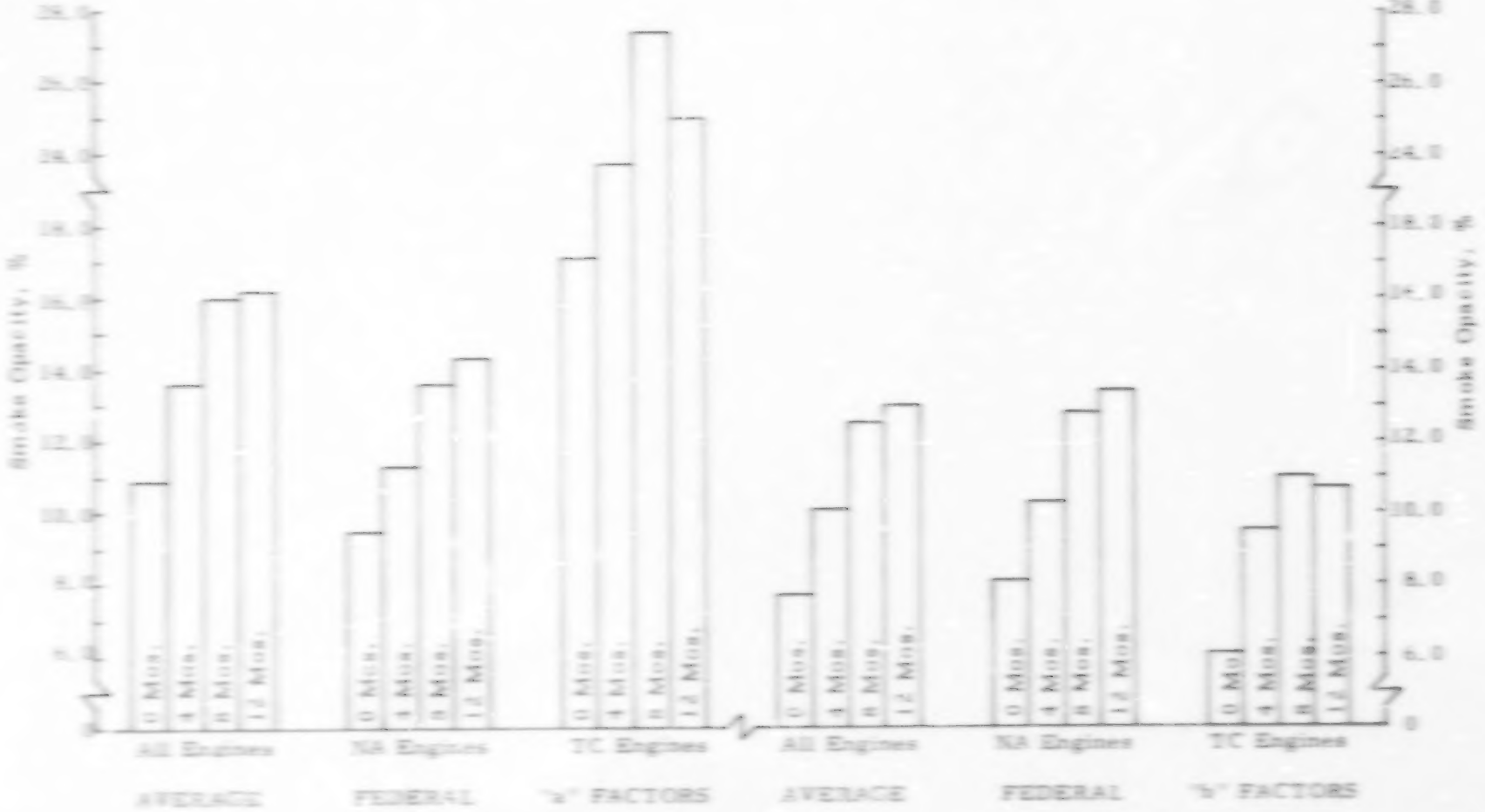


FIGURE 11. AVERAGE "a" AND "b" FACTORS FOR ALL FLEET ENGINES, NATURALLY ASPIRATED FLEET ENGINES, AND TURBOCHARGED FLEET ENGINES

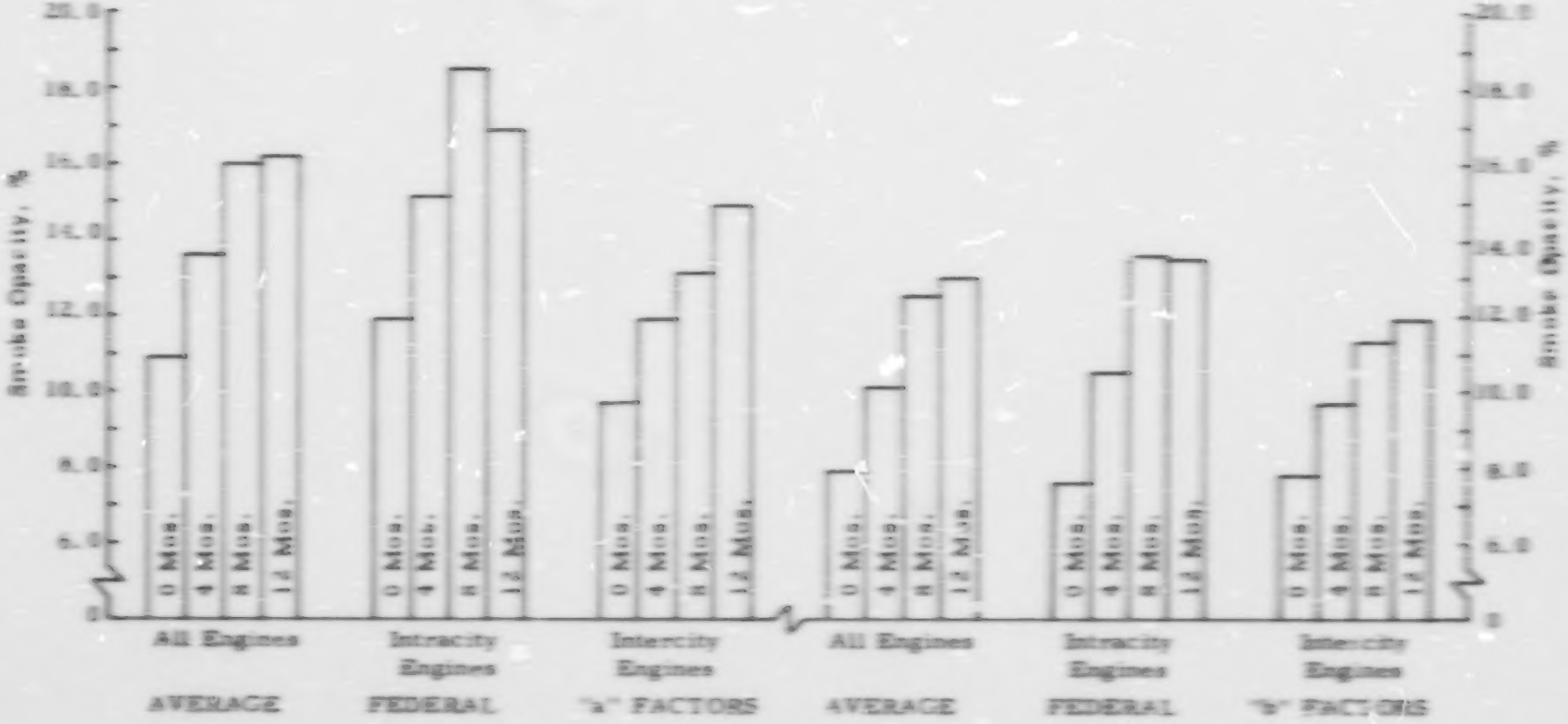


FIGURE 54. AVERAGE "a" AND "b" FACTORS FOR ALL FLEET ENGINES, INTRACITY FLEET ENGINES, AND INTERCITY FLEET ENGINES

VI. RESULTS OF GASEOUS EMISSIONS TESTS

Fifty-nine of the 64 vehicles in the test fleet underwent the chassis dynamometer version of the California ARB emissions test. (The five commercial garbage trucks could not be tested because of tire overheating problems during the test.) The results in this section are grouped under two major headings, two-cycle engines and four-cycle engines. This division is a matter of convenience only, and is not meant to imply a comparison of the emissions of the two types of engines.

The data include brake specific quantities of HC, CO, NO_2, and HC + NO_2, and the values are the average of all tests (usually two) of each engine/vehicle. The data are principally compared to the 1973 and 1975 California standards for BSCO and BSHC + $BSNO_2$. No information regarding future Federal standards for heavy-duty diesel engines was available at the time this report was written. A simple statistical analysis, providing the average, mean and standard deviations, and coefficient of variation, has been performed on the data for each engine group, and the results presented in the tables. Another statistical analysis, which considers the fleet as a whole, appears later in this section.

A Two-Cycle Engines

Table 15 contains the brake specific emissions data for the Detroit Diesel engines of the "71" and "53" series. The brake specific values for the five 8V engines with separate dual exhaust outlets were obtained by performing one test for each engine bank and then averaging the two sets of data. This approach is justified since the brake specific results are based on mass flow rates that can be combined and averaged. The first three sets of bars in Figures 55, 56, 57, and 58 illustrate the minimum, maximum, and average values of BSHC, BSCO, $BSNO_2$, and BSHC + $BSNO_2$, respectively, for the two-cycle engines.

These engines were generally characterized by low BSHC and high $BSNO_2$. (It should be noted that only NO was measured directly; the $BSNO_2$ values were obtained by multiplying BSNO values by 1.533, the approximate ratio of the respective molecular weights.) The 8V engines had the lowest BSHC, followed in order by the 6V-71 and 6V-53 models. The 6V-71 engines generally had the lowest $BSNO_2$ and the 6V-53 the highest, with the 8V engine between these two extremes. Seven of the ten 6V-71 engines met the 1973 California limit of 16 g/bhp-hr of HC + NO_2, while none of the 6V-53 models were under this particular limit. Of the six 8V engines, only the derated version (290 hp, 60-mm^3 injectors) in the intercity bus met the 1973 standard for brake specific HC + NO_2. The 1975 limit of 5 g/bhp-hr of these same contaminants was substantially lower than the current emission levels of these two-cycle engines (Figure 58). The 8V engines generally had the lowest BSCO and the 6V-71 models had the highest. California's 1973 and 1975 limits on CO of 40 and 25 g/bhp-hr, respectively,

TABLE 15. BRAKE SPECIFIC EMISSIONS FOR VEHICLES POWERED BY TWO-CYCLE ENGINES

No.	Mileage	g/(bhp-hr) HC	CO	NO_x	CO_2	HC + NO_x
Engine: Detroit Diesel 6V-71N (1.88 65 Injectors)						
Vehicle: GM Intracity Bus						
815	58,481	1.67	7.54	9.54	14.51	16.10
816	44,560	0.97	7.06	7.85	14.01	13.00
817	36,948	1.55	7.93	8.04	12.51	13.80
818	61,200	1.15	10.42	8.86	13.59	14.74
819	62,542	1.08	11.17	8.13	12.47	13.55
820	55,598	0.96	9.75	9.69	14.88	15.84
821	58,117	1.04	9.48	9.10	13.96	14.97
822	59,185	1.15	10.51	7.79	15.01	16.16
823	59,855	1.10	9.34	9.55	15.26	16.37
824	57,223	1.07	9.57	9.72	14.90	15.70
Average		1.17	9.39	9.07	13.91	15.03
Mean Deviation		0.18	0.93	0.68	1.04	1.04
Standard Deviation		0.25	1.24	0.90	1.23	1.24
Coefficient of Variation		0.21	0.13	0.09	0.09	0.08
Engine: Detroit Diesel 8V-71N (1.88 65 Injectors)						
Vehicle: Intercity Truck-Tractor						
104	59,990	0.89	7.99	11.08	16.97	17.88
105	64,855	0.76	6.71	13.82	16.60	17.36
106	61,405	0.78	7.02	10.16	15.58	16.34
107	48,487	0.85	6.58	9.90	15.17	16.02
405	61,050	0.86	6.98	11.08	18.36	19.22
Average		0.82	7.05	10.79	16.54	17.37
Mean Deviation		0.05	0.36	0.61	0.93	0.95
Standard Deviation		0.06	0.53	0.82	1.26	1.28
Coefficient of Variation		0.07	0.07	0.08	0.08	0.07
Engine: Detroit Diesel 8V-71N (1.88 60 Injectors)						
Vehicle: Intercity Bus						
501	55,234	0.49	7.16	4.89	7.50	7.59
Engine: Detroit Diesel 6V-53N (1.88 45 Injectors)						
Vehicle: Refrigerated Van						
1	22,754	1.48	9.48	12.10	18.55	20.04
5	20,402	1.66	7.30	10.98	16.83	18.49
8	26,664	1.86	10.02	12.87	19.73	21.59
10	23,926	1.56	8.40	11.58	17.63	19.19
16	21,069	1.64	8.58	11.64	17.84	19.48
Average		1.64	8.76	11.82	18.12	19.76
Mean Deviation		0.10	0.80	0.51	0.82	0.84
Standard Deviation		0.14	1.05	0.71	1.09	1.17
Coefficient of Variation		0.09	0.12	0.06	0.06	0.06

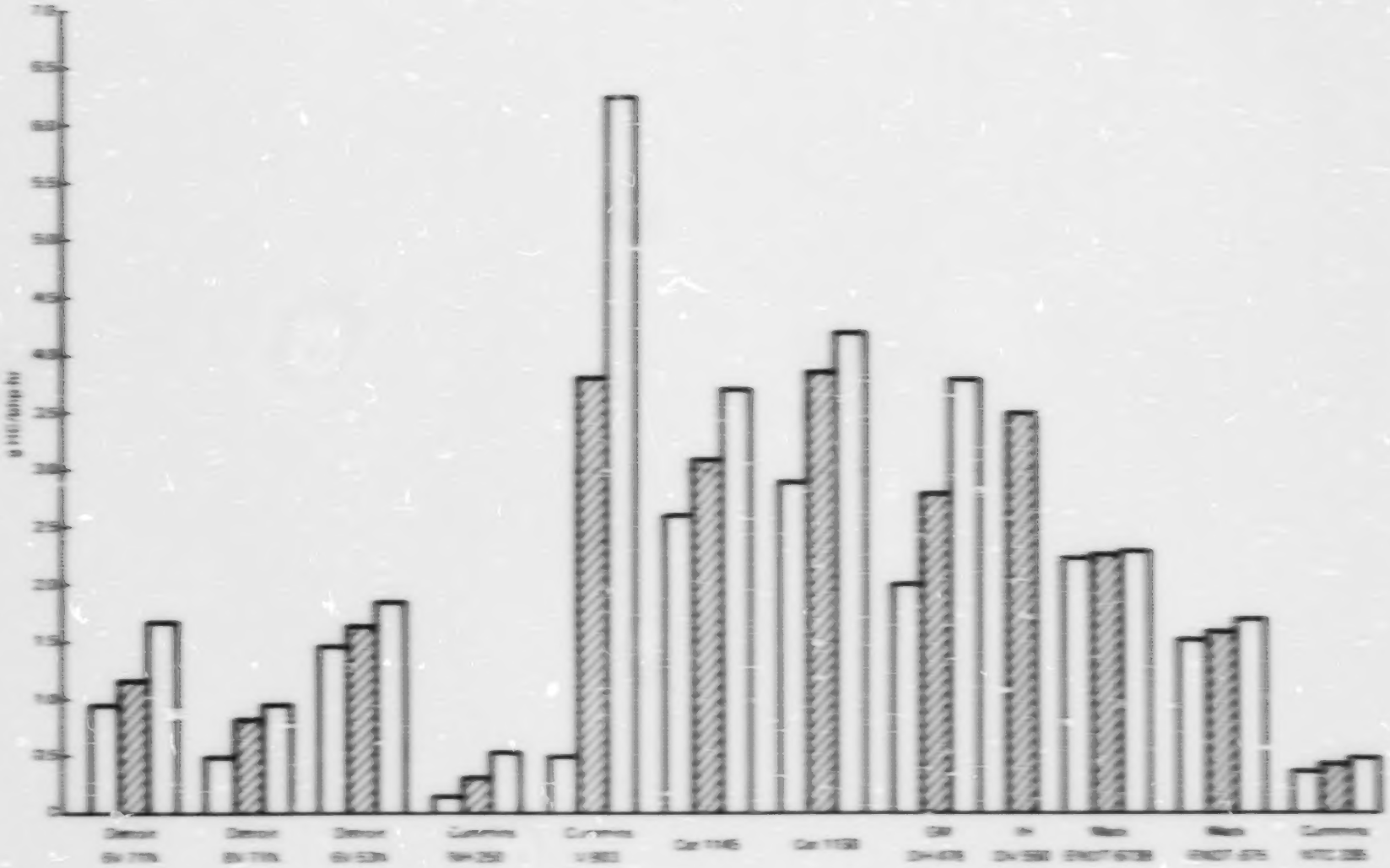


FIGURE 55. MINIMUM, MAXIMUM, AND AVERAGE BRAKE SPECIFIC HC FOR 5+ HEAVY-DUTY DIESEL ENGINES

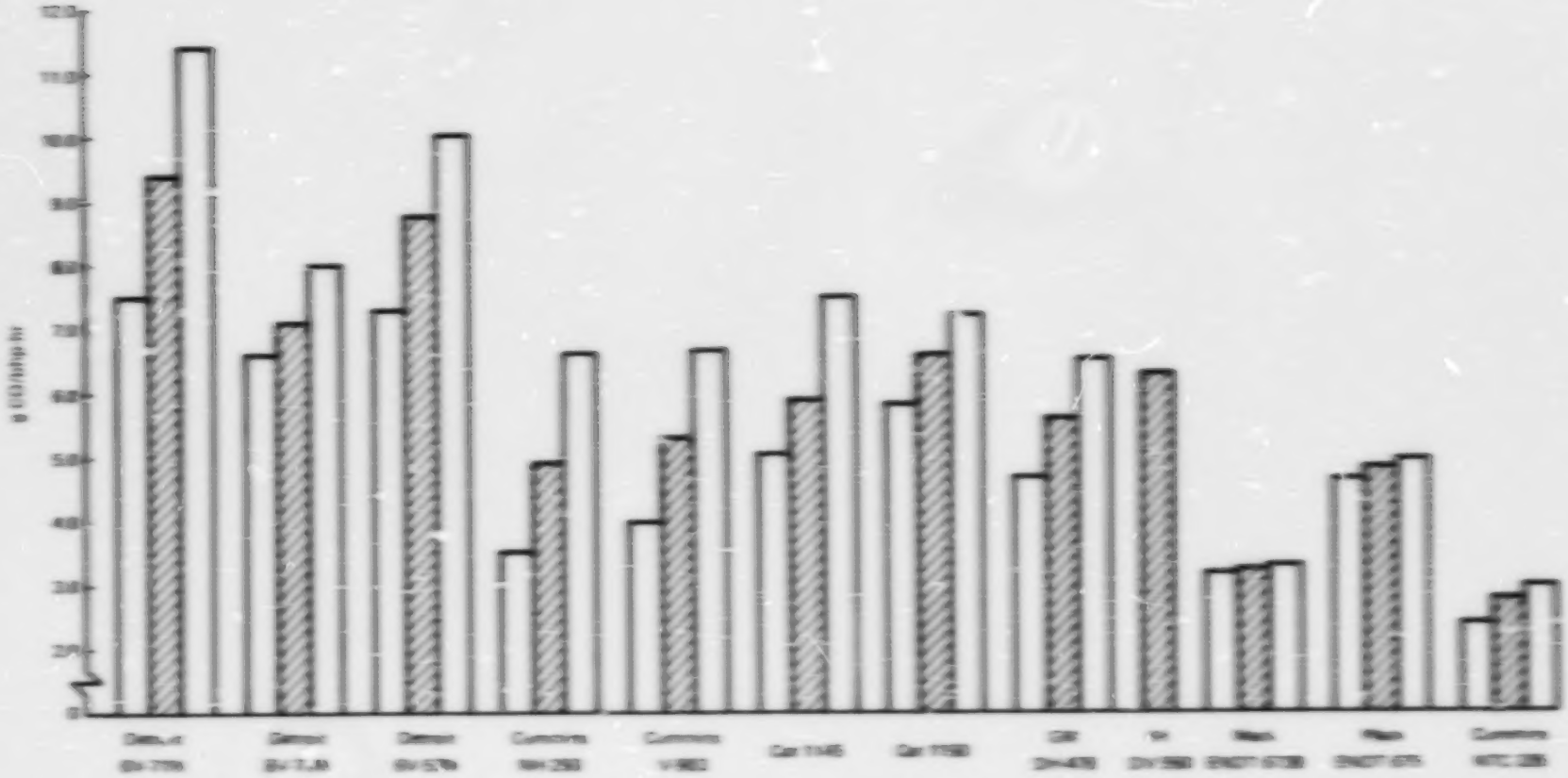


FIGURE 34. MINIMUM, MAXIMUM, AND AVERAGE BRAKE SPECIFIC CO FOR 54 HEAVY-DUTY DIESEL ENGINES

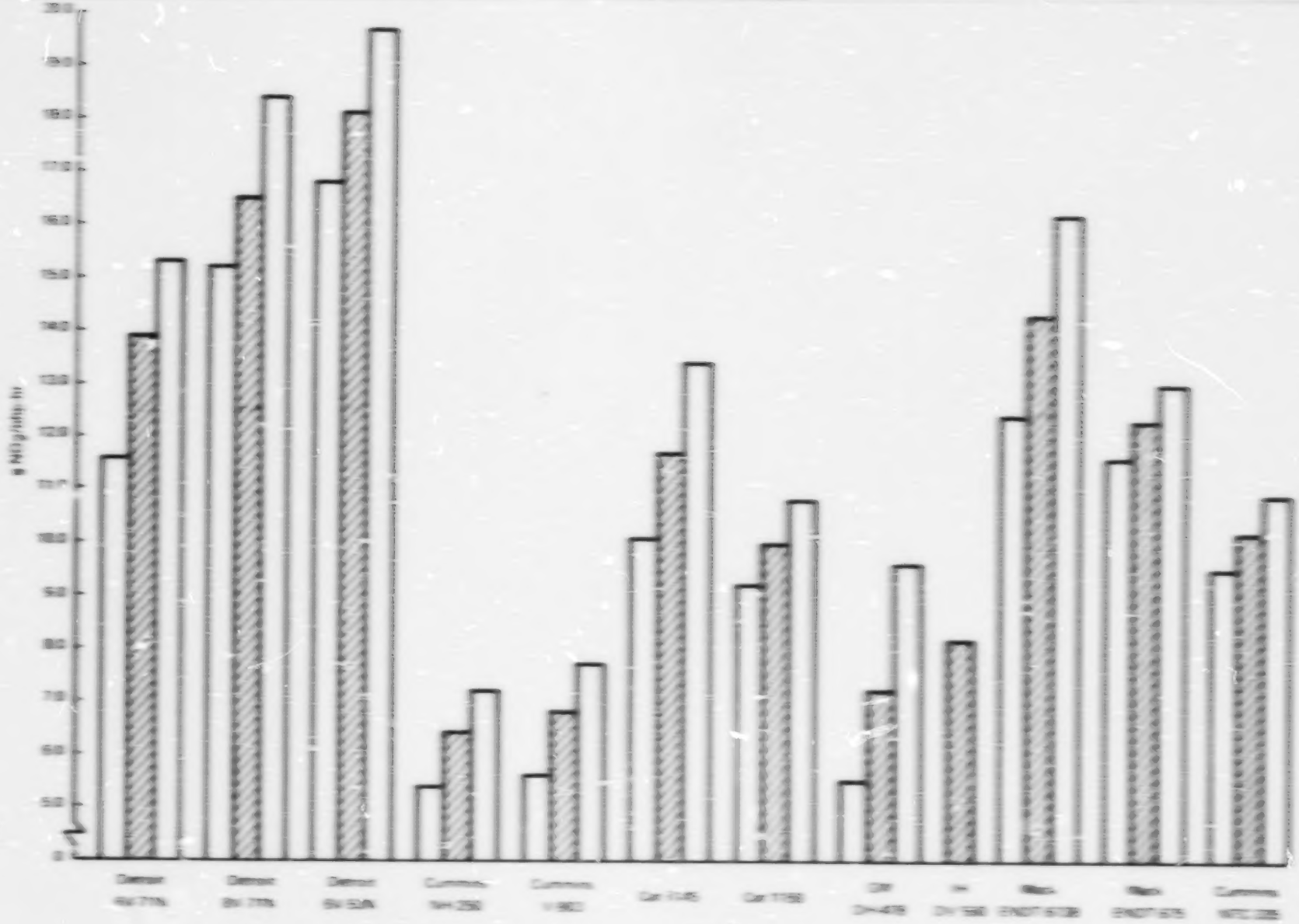


FIGURE 57. MINIMUM, MAXIMUM, AND AVERAGE BRAKE SPECIFIC NOx FOR 59 HEAVY-DUTY DIESEL ENGINES

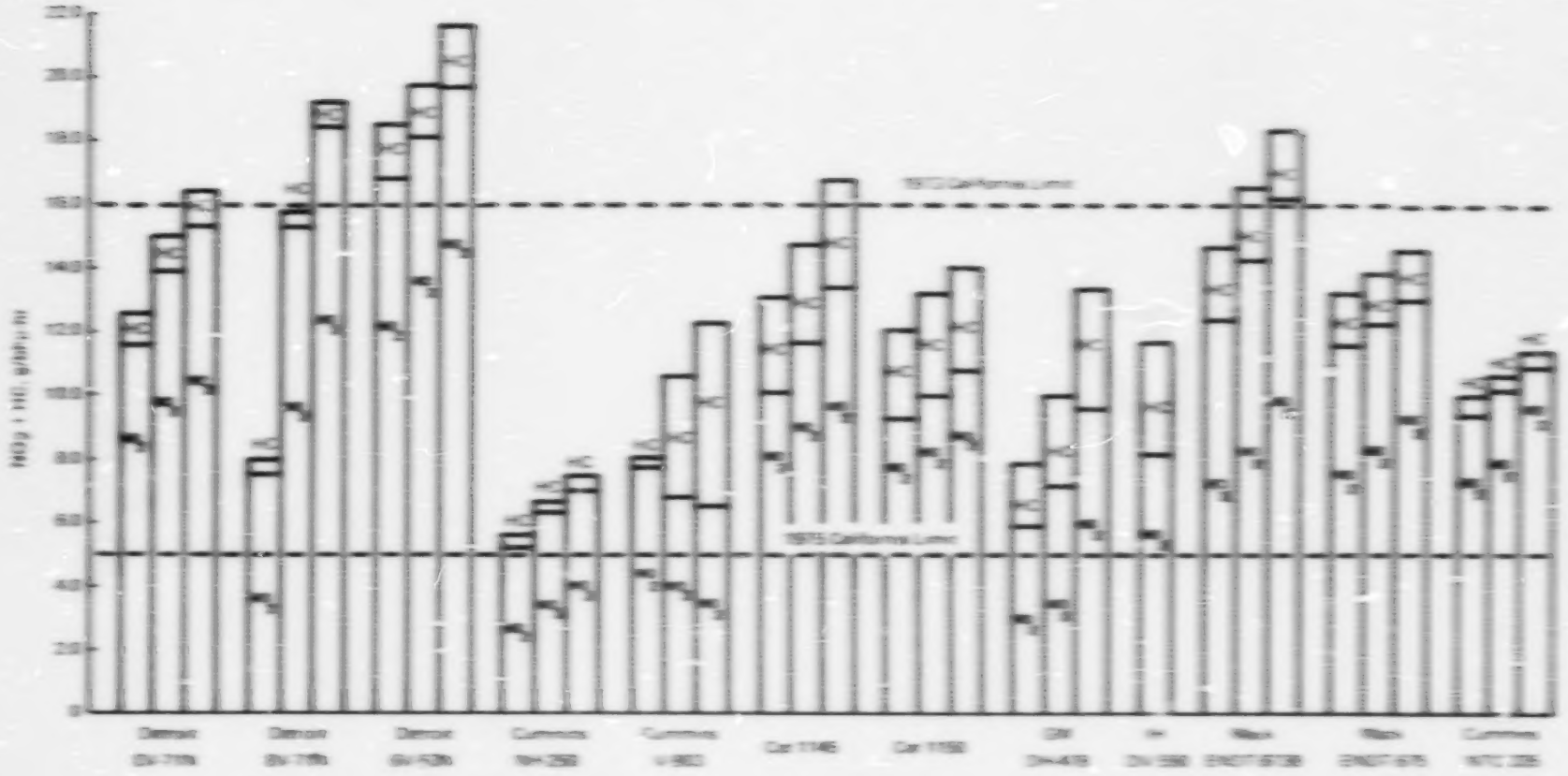


FIGURE 58. MINIMUM, MAXIMUM, AND AVERAGE BSHC + $BSNO_x$ FOR 5[a] HEAVY-DUTY DIESEL ENGINES

were based on spark-ignition gasoline engines and hence are not really applicable to diesel engines.

These two-cycle engines, although of the same basic design, have different operating speeds and injector sizes that may account for some of the observed differences in their brake specific emissions. However, it it is not certain what the exact effects these variables have on the engines' emission characteristics. The various operating (and, hence, test) speeds of these engines are given in Table 2 of Section III. However, the 6V-71 engines were tested at 1000 and 1600 rpm, speeds which more adequately reflect typical engine operation in an intracity bus. This is the only instance in this project where the engine test speeds used were different from those specified in the ARB procedure. The injector sizes with which the two-cycle test engines were equipped are given in Table 15 of this section.

B. Four-Cycle Engines

The brake specific data for the naturally aspirated and turbocharged four-cycle test engines is presented in Table 16 and illustrated in Figures 55 to 58, inclusive.

The Cummins NH-250 engines exhibited low brake specific values in every category of gaseous emissions. In fact, these engines had the lowest BSHC and $BSNO_2$ of any type of engine in the project. The average BSHC + $BSNO_2$ value of 6.68 easily meets the 1973 California limit of 16 g/bhp-hr, and comes close to the 5 g/bhp-hr limit for 1975. These engines also had the lowest average BSCO value of any naturally aspirated engine tested. The low BSCO values are somewhat surprising in view of the higher-than-normal fuel rates of most of these engines (see Section IV). An increase in fuel rate usually leads to increased CO output.

The brake specific data for the Cummins V-903 engines require some preliminary remarks. It was mentioned previously (Section IV) that the V-903 engines tested were of two basic configurations. One engine (Truck No. 415) was rated 320 hp at 2600 rpm. The four remaining engines were rated 240 hp at 2400 rpm. This lower rating, a standard option offered by Cummins, is obtained by reducing the injection pump delivery pressure (and, hence, the fuel rate) and by modifying the high speed governor setting.

The 320-hp engine had brake specific emissions similar to those of the NH-250 engines. However, the derated V-903 models had BSHC values up to 12 times that of the 320-hp engine. Conversation with the engine manufacturer produced several possible explanations for this anomoly, such as a cracked injector cup, an injector tip with a partially blocked orifice, or some other condition which would cause fuel to be sprayed directly on the cylinder wall or piston crown. It was decided, with the concurrence of the Project Officer, not to delve into the exact cause of the problem.

TABLE 16. BRAKE SPECIFIC EMISSIONS FOR VEHICLES POWERED BY FOUR-CYCLE ENGINES

Engine: Cummins NH-250
Vehicle: Intercity Truck-Tractor

No.	Mileage	g/bhp-hr NMHC	NMCO	NOx	NMHC + NOx
41	38,316	0.38	6.60	4.15	6.36	5.74
42	71,849	0.32	5.04	4.36	6.68	7.00
62	161,604	0.48	5.86	4.08	6.45	6.54
15741	76,654	0.30	4.65	4.64	7.08	7.38
15744	74,104	0.40	4.15	4.63	7.13	7.53
15745	112,044	0.16	5.18	4.04	6.19	6.35
15746	101,787	0.31	5.66	4.14	6.65	6.96
24618	13,168	0.57	3.54	4.68	6.56	6.25
26153	17,363	0.39	4.63	4.53	5.81	5.65
26154	15,787	0.53	4.42	3.44	5.27	5.00
Average		0.33	4.90	4.15	6.36	6.66
Mean Deviation		0.06	0.78	0.30	0.47	0.47
Standard Deviation		0.10	0.97	0.41	0.63	0.61
Coefficient of Variation		0.30	0.20	0.10	0.10	0.09

Engine: Cummins V-903
Vehicle: Intercity Truck-Tractor

815	65,515	0.52	5.32	5.04	7.71	9.45
966	41,047	1.04	5.57	4.56	6.93	8.83
968	47,079	6.26	5.92	3.66	5.61	11.87
970	43,407	4.60	4.64	4.72	7.24	11.84
972	40,865	5.84	6.66	4.24	6.47	12.29
Average		3.84	5.30	4.44	6.84	10.64
Mean Deviation		2.10	0.60	0.42	0.61	1.56
Standard Deviation		2.52	1.05	0.57	0.84	1.91
Coefficient of Variation		0.66	0.20	0.13	0.12	0.18

Engine: Cummins NTC-335
Vehicle: Intercity Truck-Tractor

20	65,013	0.50	2.97	6.17	9.46	9.96
144	67,491	0.38	2.80	6.97	10.68	11.06
458	126,772	0.48	2.40	7.19	10.88	11.36
6213	114,382	0.49	2.96	6.40	9.91	10.40
Average		0.46	2.78	6.66	10.23	10.67
Mean Deviation		0.04	0.19	0.38	0.57	0.54
Standard Deviation		0.06	0.27	0.45	0.68	0.65
Coefficient of Variation		0.13	7.10	0.07	0.07	0.06

Engine: Mack ENDT 676
Vehicle: Intracity Truck-Tractor

60132	10,490	2.29	3.19	8.11	12.44	14.73
60134	9,568	2.25	3.20	10.54	16.16	18.41
Average		2.27	3.25	9.32	14.30	16.57

Engine: Mack ENDT 675
Vehicle: Intercity Truck-Tractor

1	109,851	1.70	4.80	7.54	11.56	13.26
5	115,283	1.52	4.98	8.59	13.03	14.55
Average		1.61	4.89	8.02	12.29	13.90

TABLE 16. BRAKE SPECIFIC EMISSIONS FOR VEHICLES POWERED BY FOUR-CYCLE ENGINES (Cont'd)

No.	Mileage	g/bhp-hr BSHC	BSCO	BSNO$_x$	BSHC + BSNO$_x$
Engine: Caterpillar 1145					
Vehicle: Intracity Delivery Truck					
507	7,222	2.62	5.59	7.35	11.22	13.84
510	6,222	3.48	6.22	8.82	13.17	16.85
512	3,438	2.66	5.05	7.38	11.32	13.98
519	17,033	2.98	5.18	6.59	10.10	13.08
527	4,006	3.70	7.50	8.09	12.40	16.10
Average		3.09	5.91	7.62	11.68	14.77
Mean Deviation		0.40	0.76	0.65	1.00	1.36
Standard Deviation		0.49	1.00	0.85	1.30	1.62
Coefficient of Variation		0.16	0.17	0.11	0.11	0.11
Engine: Caterpillar 1150						
Vehicle: Intracity Truck-Tractor						
880	10,223	3.36	5.84	7.01	10.75	14.11
881	11,781	3.02	6.39	7.04	10.79	13.81
883	11,479	4.20	7.25	6.40	9.81	14.01
884	21,645	2.89	6.98	6.01	9.22	12.11
885	12,752	3.38	6.62	6.04	9.26	12.64
Average		3.37	6.62	6.50	9.97	13.34
Mean Deviation		0.34	0.40	0.42	0.64	0.76
Standard Deviation		0.52	0.54	0.51	0.78	0.90
Coefficient of Variation		0.15	0.08	0.08	0.08	0.07
Engine: GM DH-478						
Vehicle: Intracity Truck-Tractor						
118	8,578	3.26	6.36	3.58	5.49	8.75
133	10,602	2.16	4.93	5.24	8.00	10.16
137	2,844	3.80	4.72	6.27	9.61	13.41
190	3,200	2.02	6.16	3.83	5.87	7.89
Average		2.81	5.59	4.72	7.24	10.05
Mean Deviation		0.72	0.77	1.02	1.56	1.73
Standard Deviation		0.86	0.90	1.26	1.93	2.43
Coefficient of Variation		0.31	0.16	0.27	0.27	0.24
Engine: International Harvester DV550B						
Vehicle: Dump Truck						
631	17,655	3.52	6.32	5.36	8.21	11.74

since to do so would have involved removal of the injectors and cylinder heads. Such a step would have been undesirable as far as the smoke surveillance tests were concerned. In spite of these very high BSHC values, the engines met the 1973 standard for BSHC + $BSNO_2$, mainly because of low $BSNO_2$ values. Brake specific CO was comparable to that of the NH-250 engines.

The Cummins NTC-335 engines had the low BSHC of the NH-250; however, the turbocharged engines had about 50 percent more $BSNO_2$ than the naturally aspirated engines. All four of the NTC-335 models met the 1973 California limit for BSHC + $BSNO_2$. These engines had the lowest BSCO of any engine in the project.

The two Mack ENDT 674B engines also had very low BSCO, but their BSHC and $BSNO_2$ values were the highest of any turbocharged engines in the project. Hence, the sum of these two latter quantities was high, and one engine was over the 1973 California limit. The two ENDT 675 engines tested for gaseous emissions had lower average brake specific HC and NO_2, and higher BSCO, than the 674B engines. Both of the 675 models were under the 1973 limit.

The Caterpillar 1145 and 1150 engines had high average BSHC (greater than 3 g/bhp-hr) and moderately high $BSNO_2$. Two of the five 1145 models were over the 1973 California limit for the sum of these contaminants, although the average for the five was under this limit. All five of the 1150 engines were under the limit.

The GM DH-478 engines also had high BSHC, but the $BSNO_2$ values were low. The average sum of these two quantities was just over 10 g/bhp-hp and hence was lower than for any other engine group except the Cummins NH-250. All four of the DH-478 engines met the 1973 California limit. The lone IHC engine in the test fleet produced over 3.5 g/bhp-hr of HC, but had only 8.2 g/bhp-hr of NO_2. Thus the engine was well below the 1973 standard.

C. Statistical Analysis of Gaseous Emissions Test Data

The brake specific emissions data in this section were analyzed to obtain basic statistical quantities such as the range and frequency distributions, the means or averages, the mean and standard deviations, and the coefficients of variation. The results of this analysis are contained in Table 17.

BSHC--The relative frequency distribution (Figure 59) has its peak in the interval from 0 to 1 g/bhp-hr, then decreases through the higher-valued intervals. This peak is the result of the low BSHC of the Cummins NH-250 and NTC-335 engines and Detroit Diesel 8V-71 engines. The interval from 1 to 2 g/bhp-hr contains most of the values of the Detroit Diesel 6V-71 and 6V-53 engines, and the Mack ENDT 675 engines. The Mack

TABLE 17. STATISTICAL ANALYSIS OF BRAKE SPECIFIC EMISSIONS

BSHC

g/bhp-hr Interval	Frequency	Frequency Percentage	Cumulative Percentage
0 to 0.99	11	32.0	32.0
1 to 1.99	16	47.0	79.0
2 to 2.99	3	11.8	79.8
3 to 3.99	4	11.8	91.8
4 to 4.99	1	2.9	94.6
5 to 5.99	1	2.9	97.5
6 to 6.99	1	2.9	100.0

Range of BSHC Values: 0.15 to 6.16 g/bhp-hr
Average BSHC: 1.79 g/bhp-hr
Mean Deviation: 1.13
Standard Deviation: 1.41
Coefficient of Variation: 0.91

BSCO

g/bhp-hr Interval	Frequency	Frequency Percentage	Cumulative Percentage
4 to 4.99	5	14.4	14.4
5 to 5.99	10	30.3	45.7
6 to 6.99	11	25.6	71.3
7 to 7.99	4	11.5	82.8
8 to 8.99	3	11.5	94.2
10 to 11.99	2	5.8	100.0

Range of BSCO Values: 4.30 to 11.17 g/bhp-hr
Average BSCO: 6.34 g/bhp-hr
Mean Deviation: 1.14
Standard Deviation: 1.38
Coefficient of Variation: 0.34

BSNO$_x$

g/bhp-hr Interval	Frequency	Frequency Percentage	Cumulative Percentage
5 to 5.99	15	44.0	44.0
7 to 7.99	4	11.8	55.8
9 to 10.99	11	32.6	88.4
11 to 12.99	4	11.5	100.0
13 to 14.99	2	11.3	77.7
15 to 16.99	4	11.8	91.5
17 to 18.99	2	5.8	98.3
19 to 20.99	1	1.7	100.0

Range of BSNO$_x$ Values: 5.37 to 19.71 g/bhp-hr
Average BSNO$_x$: 11.14 g/bhp-hr
Mean Deviation: 3.36
Standard Deviation: 4.04
Coefficient of Variation: 0.36

BSHC + BSNO$_x$

g/bhp-hr Interval	Frequency	Frequency Percentage	Cumulative Percentage
5 to 5.99	3	11.9	11.9
7 to 8.99	4	11.8	23.8
9 to 10.99	3	9.1	32.8
11 to 12.99	4	11.8	44.6
13 to 14.99	10	25.3	69.9
15 to 16.99	3	10.2	80.2
17 to 18.99	4	6.8	87.0
19 to 20.99	4	6.8	93.8
21 to 22.99	1	1.7	100.0

Range of BSHC + BSNO$_x$ Values: 5.65 to 21.59 g/bhp-hr
Average BSHC + BSNO$_x$: 12.88 g/bhp-hr
Mean Deviation: 3.83
Standard Deviation: 4.11
Coefficient of Variation: 0.32

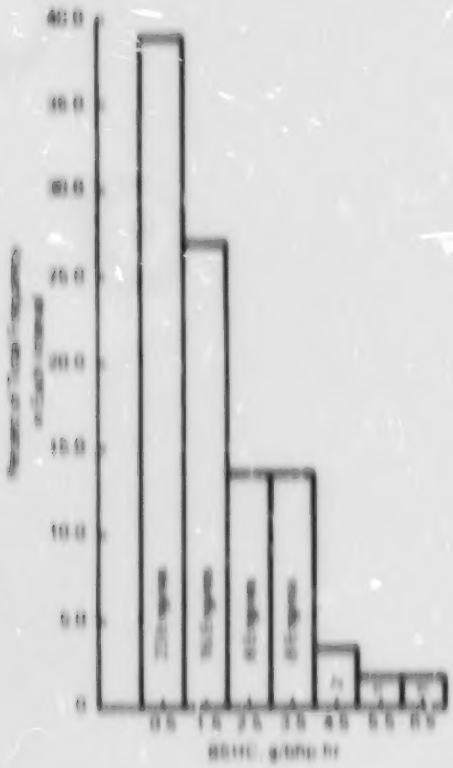


FIGURE 59. RELATIVE FREQUENCY DISTRIBUTION OF BRAKE SPECIFIC HC VALUES

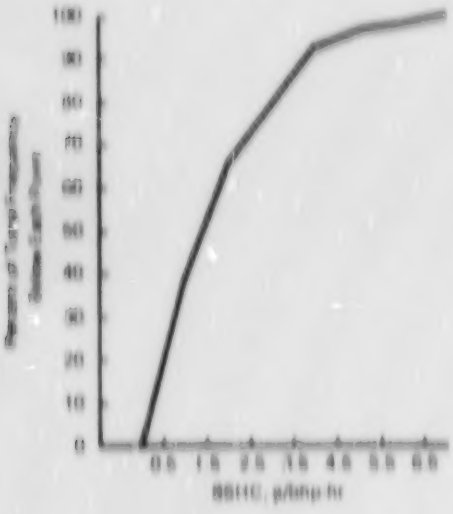


FIGURE 60. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF BRAKE SPECIFIC HC VALUES

ENDT 673B engines and several of the midrange engines (Caterpillar 1145 and 1150, and GM DH-478) have values in the interval from 2 to 3 g/bhp-hr. The rest of the midrange engines have BSHC values of 3 to 4 g/bhp-hr. The intervals above 4 g/bhp-hr contain the very high values of the derated Cummins V-903 engines.

The cumulative frequency distribution (Figure 60) is provided to show the percentage of fleet vehicles with BSHC values below or above a given point. The first, second, and third quartiles of these data are approximately 0.5, 1.5, and 2.7 g/bhp-hr, respectively, and divide the data into four equal parts. The range of the BSHC values is 0.16 to 6.26 g/bhp-hr, and the average value is a low 1.75 g/bhp-hr. The standard deviation is 1.41, and yields a large coefficient of variation 0.81. Hence, the data have a high degree of both absolute and relative variation. About 71 percent of the data fell within one standard deviation of the mean, i.e., in the range 0.34 to 3.16 g/bhp-hr.

BSCO--The relative frequency distribution (Figure 61) has its peak in the interval from 6 to 8 g/bhp-hr, which contains the BSCO values for the Detroit Diesel 8V-71 engines, and several of the midrange Caterpillar 1150 and GM DH-478 engines. The interval from 4 to 6 g/bhp-hr has most of the values from the Cummins NH-250 and V-903 engines, the Mack ENDT 675, and the Caterpillar 1145 engines. The lowest interval, from 2 to 4 g/bhp-hr, contains data from the turbocharged Cummins NTC-335 and Mack ENDT 673B engines. The Detroit Diesel 6V-71 and 6V-53 engines populate the intervals above 8 g/bhp-hr. The cumulative frequency distribution is shown in Figure 62. First, second, and third quartiles are approximately 4.7, 6.3, and 7.8 g/bhp-hr, respectively.

The BSCO values have a range of 2.40 to 11.37 g/bhp-hr, with an average of 6.34 g/bhp-hr. The standard deviation is 2.14, so that these data have more absolute variation than the BSHC data. However, the coefficient of variation for the BSCO is 0.34, less than half the relative variation of the HC values. About 68 percent of the BSCO data lies within one standard deviation of the mean, i.e., in the range from 4.20 to 8.48 g/bhp-hr.

$BSNO_x$--The peak of the relative frequency distribution (Figure 63) occurs in the interval from 5 to 7 g/bhp-hr, which contains most of the data for the Cummins NH-250 and V-903 engines. A slightly smaller peak in the interval from 9 to 11 g/bhp-hr is due to the data from the Cummins NTC-335 and Caterpillar 1150 engines. The Caterpillar 1145 and Mack ENDT engines have values in the 11 to 13 g/bhp-hr range. The intervals above 13 g/bhp-hr cover the values of the Detroit Diesel two-cycle engines. The cumulative frequency distribution is illustrated in Figure 64, and estimated first, second, and third quartiles are 7.3, 10.5, and 14.9 g/bhp-hp, respectively.

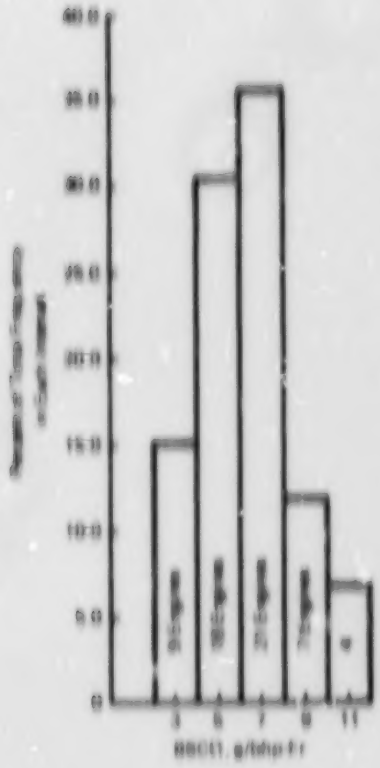


FIGURE 61. RELATIVE FREQUENCY DISTRIBUTION OF BRAKE SPECIFIC CO VALUES

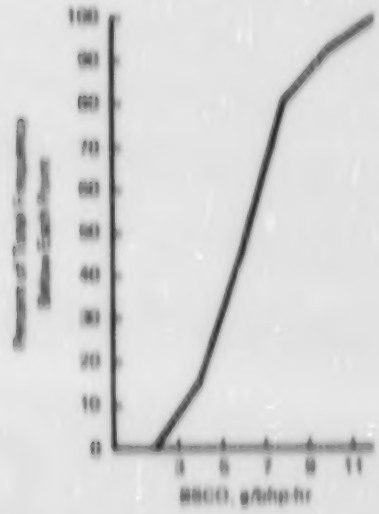


FIGURE 62. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF BRAKE SPECIFIC CO VALUES

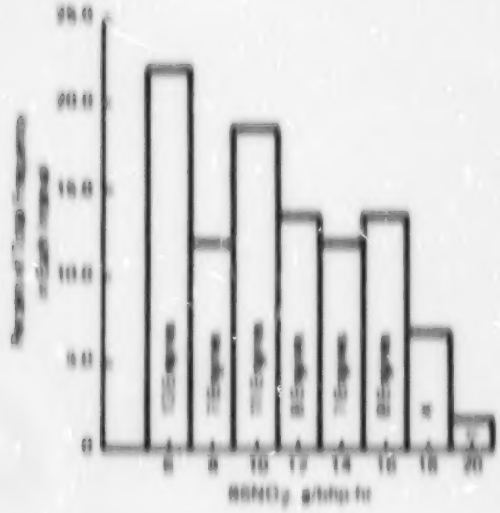


FIGURE 63. RELATIVE FREQUENCY DISTRIBUTION OF BRAKE SPECIFIC NO_2 VALUES

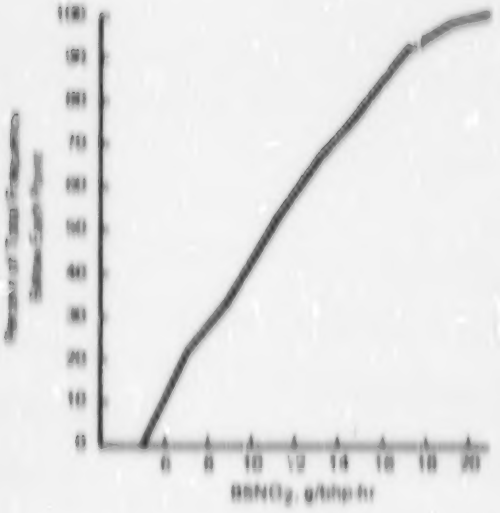


FIGURE 64. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF BRAKE SPECIFIC NO_2 VALUES

The $BSNO_2$ data have a range of 5.27 to 19.73 g/bhp-hr, and an average of 11.1 g/bhp-hr. The standard deviation of 4.04 indicates a large absolute variation in the data, but the coefficient of variation is a reasonable 0.36. Approximately 58 percent of the data are within one standard deviation of the mean, i.e., in the range 7.1 to 15.18 g/bhp-hr.

BSHC + $BSNO_2$--The relative frequency has its peak in the interval from 14 to 15 g/bhp-hr, with smaller, but still significant, peaks in intervals to the immediate right and left (Figure 65). The intervals from 13 to 17 g/bhp-hr contain the data from the Detroit Diesel "71" series engines, the Caterpillar 1145 midrange engines, and the turbocharged Mack engines. The interval from 11 to 13 g/bhp-hr has values from the Cummins NTC-335, Cummins V-903, Caterpillar 1150, and IH DV 550B engines. The lowest intervals, from 5 to 9 g/bhp-hr, contain the data from the Cummins NH-250 engines. At the other extreme, the intervals above 17 g/bhp-hr, are found the values from the Detroit Diesel 8V-71 and 6V-53 engines.

The cumulative frequency distribution is shown in Figure 66. About 73 percent of the engines tested met the 1973 California limit of 16 g/bhp-hr, while none were below the 1975 limit of 5 g/bhp-hr. The first, second, and third quartiles are 8.8, 13.4, and 16.1 g/bhp-hr, respectively. These data have a range from 5.65 to 21.59 g/bhp-hr, and an average of 12.88 g/bhp-hr. The standard deviation is 4.13, which is only slightly larger than that of the $BSNO_2$ alone. The coefficient of the variation is 0.32 and indicates the lowest relative variation of the brake specific data. Approximately 63 percent of these data lie within one standard deviation of the mean, or in the range 8.75 to 17.01 g/bhp-hr.

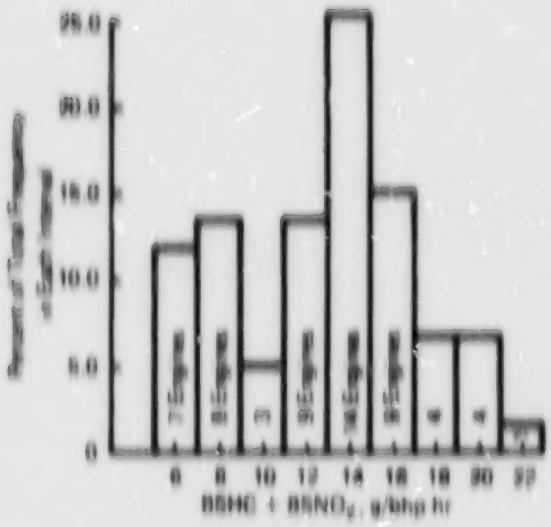


FIGURE 65. RELATIVE FREQUENCY DISTRIBUTION OF BSHC + BSNO$_x$ VALUES

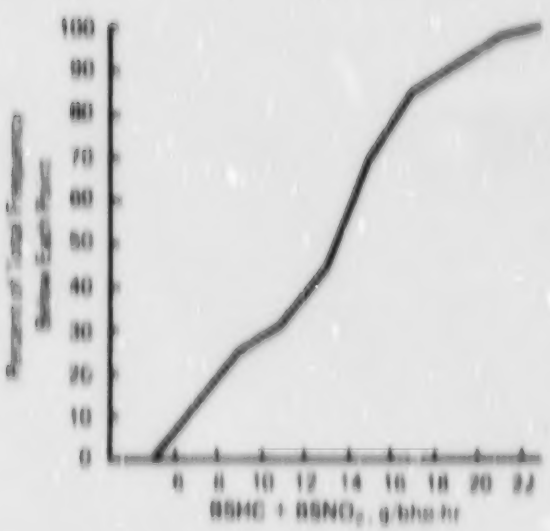


FIGURE 66. RELATIVE CUMULATIVE FREQUENCY DISTRIBUTION OF BSHC + BSNO$_x$ VALUES

VII. CONTINUATION OF PROJECT

In January, 1973, the contract for this project was modified to extend the test period from 18 months to 24 months for certain vehicles in the fleet. These vehicles are those that had accumulated less than 100,000 total odometer miles at the end of 18 months of test operation. Additional smoke inspections will be performed at four-month intervals, until the vehicles in question reach 100,000 vehicle miles or 24 months of test operation, whichever occurs first. The test plan provides for approximately 80 tests in the second year of the project. The fleet vehicles included in this second phase of the project, and a tentative schedule of their smoke inspections, are presented in Table 18. Note that all of these vehicles are in intracity service, with the exception of the three truck-tractors powered by Cummins NH-250 engines. It is anticipated that most of these vehicles will not reach the 100,000-mile cutoff point in this second year of operation. The results of the fifth-, sixth-, and seventh-round tests will be joined with the results presented in this interim report to form the final report for the project. All work performed under the original contract and the modification are to be completed by June 29, 1973.

TABLE 18. TENTATIVE TEST SCHEDULE FOR SECOND YEAR OF PROJECT

Engine/Vehicle	Original No. In Fleet	Number of Vehicles Tested per Inspection		
		5th Round (16 mos.)	6th Round (20 mos.)	7th Round (24 mos.)
Detroit Diesel 6V-71N/Bus	10	4	0	0
Detroit Diesel 6V-53N/Van	5	5	5	4
Cummins NH-250/Truck-Tractor	10	3	0	0
Mack ENDT 675/Garbage Truck	5	5	4	4
Mack ENET 673B/Truck-Tractor	2	2	2	2
Caterpillar 1145/Delivery Truck	5	5	5	5
Caterpillar 1150/Truck-Tractor	5	5	5	5
GM DH-478/Truck-Tractor	4	4	4	4
IHC DV-550B/Dump Truck	1	1	1	1
Totals		34	26	25

Total No. of Tests = 85

VIII. SUMMARY AND CONCLUSIONS

This project has involved a fleet of 64 vehicles powered by heavy-duty diesel engines certified under the Federal smoke compliance procedure. The vehicles were tested four times over a one-year period, at 0, 4, 8, and 12 months of test operation. The test procedure was a chassis dynamometer version of the Federal smoke compliance test, developed at SwRI. The smoke test data have been analysed to establish the correlation between observed opacity changes and time, vehicle mileage, and type of service. At one of the four scheduled smoke tests, 59 of the 64 fleet vehicles were tested for gaseous emissions of hydrocarbons (HC), carbon monoxide (CO), and nitric oxide (NO) by the California ARB 13-mode chassis dynamometer test procedure.

The following remarks summarize the results and conclusions concerning the items of work mentioned above:

(1) Only one of the sixty-four engines in the test fleet had smoke opacity above one of the 1970 Federal limits at the initial inspection (zero months of test operation).

(2) At the second-round (4-month) inspection, approximately two-thirds of these engines had Federal "a" or "b" Factors above those measured at the 0-month test. The remaining one-third of the engines produced smoke factors lower than those of the initial inspection. One "a" Factor and four "b" Factors were above the pertinent Federal limit.

(3) At the third-round (8-month) test, about 60 percent of the engines had one or both smoke factors above those of the initial test, and the remaining 40 percent of the engines had lower smoke opacity than at baseline. Two "a" Factors and nine "b" Factors were above the Federal certification limits.

(4) At the fourth-round test, following one year of normal operation, some 87 percent of the fleet engines had higher "a" or "b" Factors than at the first test. The other 13 percent of the engines produced lower smoke factors than they had initially. One "a" Factor and 12 "b" Factors were over the 1970 limits at this final inspection.

(5) In view of the above observations, it can be seen that smoke opacity tended to increase with elapsed time and mileage for most engines in the fleet. The data for various engine groups--two-cycle and four-cycle engines, naturally aspirated and turbocharged engines, and engines in intra-city and intercity service--were analysed, and it was found that the average opacity for these groups generally followed the same trend as that of the entire fleet, with a few minor exceptions.

(6) Smoke opacity generated during the full-power lugdown part of the Federal test cycle, designated as the "b" Factor, was, for this test fleet,

the most difficult to maintain below the maximum certification level (20-percent opacity). This particular limit was exceeded only by four-cycle naturally aspirated engines during this series of tests.

(7) Many turbocharged and midrange engines demonstrated very brief smoke peaks of 50- to 90-percent opacity during the first acceleration of the Federal smoke test. However, the resulting "b" Factors, which are time-averaged over a 7.5-second interval, are much lower in value than these peak opacities. The current "a" Factor limit of 40-percent opacity was exceeded only by turbocharged engines in the test fleet.

(8) The Cummins NH-250 and NTC-335 engines, along with the two-cycle 8V-71N engines, had the lowest average brake specific HC values of any engines tested. The highest BSHC values belonged to the speed-derated Cummins V-903 engines (which, in all probability, were suffering from some type of mechanical problem) and also to the midrange four-cycle engines.

(9) The four-cycle engines tested had lower BSCO than the two-cycle engines. Of these four-cycle engines, the turbocharged models generally had lower BSCO than the naturally aspirated engines. However, all engines tested were well within the 1973 and 1975 California limits of 40 and 25 g/bhp-hr, respectively.

(10) The Cummins NH-250 and V-903 models, and the GM DH-478 engines, had the lowest average brake specific NO_x, expressed here as $BSNO_2$. The turbocharged four-cycle engines generally had higher $BSNO_2$ than the naturally aspirated four-cycle engines. The highest average $BSNO_2$ belonged to the two-cycle engines in the fleet.

(11) Forty-three of the 59 engines (73 percent) tested for gaseous emissions met the 1973 California limit of 16 g/bhp-hr for BSHC + $BSNO_2$. The two-cycle engines and turbocharged Mack ENDT 673B engines had the highest average values of this sum, while the Cummins NH-250 engines had the lowest values, both individual and average. No engine met the 1975 California limit of 9 g/bhp-hr.

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APPENDIX A

FEDERAL SMOKE TEST PROCEDURE
(FEDERAL REGISTER, VOL. 35, NO. 219, NOV 10, 1970)

A-8.

FEDERAL REGISTER

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PART II

Department of Health, Education, and Welfare

Office of the Secretary

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Control of Air Pollution From New Motor Vehicles and New Motor Vehicle Engines

(iii) When the engine reaches the speed required in subdivision (ii) of this subparagraph, the throttle shall be moved rapidly to the closed position and the preselected load required to perform the acceleration in subdivision (iv) of this subparagraph shall be applied. The engine speed shall be reduced to the speed of maximum rated torque or 60 percent of rated speed, (whichever is higher), with ±50 r.p.m. Smoke emissions during this transition al mode are not used in determining smoke emissions to compare with the standard.

(iv) The throttle shall be moved rapidly to the full-throttle position and the engine accelerated against the preselected dynamometer load such that the engine speed reaches 90 to 100 percent of rated speed in 10±0 seconds.

(4) *Lugging mode.* (i) Proceeding from the acceleration mode, the dynamometer controls shall be adjusted to permit the engine to develop maximum horsepower at rated speed. Smoke emissions during this transitional mode are not used in determining smoke emissions to compare with the standard.

(ii) Without changing the throttle position, the dynamometer controls shall be adjusted gradually to slow the engine to the speed of maximum torque or to 60 percent of rated speed, whichever is higher. This engine lugging operation shall be performed smoothly over a period of 55±5 seconds. The rate of slowing of the engine shall be linear, within ±100 r.p.m.

(5) *Engine unloading.* After completion of the lugging mode in subparagraph (4)(ii) of this paragraph, the dynamometer and engine shall be returned to the idle condition described in subparagraph (1) of this paragraph.

(b) The procedures described in paragraph (a) (1) through (5) of this section shall be repeated until the entire cycle has been run three times.

§ 85.123 Dynamometer and engine equipment.

The following equipment shall be used for smoke emission testing of engines on engine dynamometers.

(a) An engine dynamometer with adequate characteristics to perform the test cycle described in § 85.122.

(b) An engine cooling system having sufficient capacity to maintain the engine at normal operating temperatures during conduct of the prescribed engine tests.

(c) A noninsulated exhaust system extending 15±3 feet from the exhaust manifold of the engine and presenting an exhaust back pressure within ±0.5 inches Hg of the upper limit at maximum rated horsepower, as established by the engine manufacturer in his sales and service literature for vehicle application. A conventional automotive muffler of a size and type commonly used with the engine being tested shall be employed in the exhaust system during smoke emission testing. The terminal 3 feet of the exhaust pipe shall be of circular cross section and be free of elbows and bends. The end of the pipe shall be cut off squarely. The terminal 3 feet of the exhaust pipe shall have a diameter in accordance with the engine being tested, as specified below:

Maximum rated horsepower	Exhaust pipe dia
Less than 101	3"
101-200	4"
201-300	5"
301 or more	6"

(d) An engine air inlet system presenting an air inlet restriction within ±1 inch of water of the upper limit for the engine operating condition which results in maximum air flow, as established by the engine manufacturer in his sales and service literature, for the engine being tested.

§ 85.124 Smoke measurement system.

(a) *Schematic drawing.* The following figure (fig. 7) is a schematic drawing of the optical system of the light extinction meter.

Figure 7. USEPA smokemeter optical system (schematic).

(b) *Equipment.* The following equipment shall be used in the system:

(1) Adapter—the smokemeter optical unit may be mounted on a fixed or movable frame. The normal unrestricted shape of the exhaust plume shall not be modified by the adapter, the meter, or any ventilation system used to remove the exhaust from the test site.

(2) Smokemeter (light extinction meter)—continuous recording. Full-flow light obscuration meter. It shall be positioned near the end of the exhaust pipe so that a built-in light beam traverses the exhaust smoke plume which leaves from the pipe at right angles to the axis of the plume. The light source is an incandescent lamp operated at a constant voltage of not less than 75 percent of the manufacturer's specified voltage. The lamp output is collimated to a beam with a nominal diameter of 1.125 inches. The angle of divergence of the collimated beam shall be within 4° included angle. A light detector, directly opposed to the light source, measures the amount of light blocked by the smoke in the exhaust. The detector sensitivity is restricted to the visual range and is comparable to that of the human eye. A collimating tube with apertures equal to the beam diameter is attached to the detector. It restricts the viewing angle of the detector to within 16° included angle. An amplified signal corresponding to the amount of light blocked is recorded continuously on a remote recorder. An air curtain across the light source and detector window assemblies may be used to minimize deposition of smoke particles on those surfaces provided that it does not measurably affect the opacity of the plume. The meter consists of two units, an optical unit and a remote control unit. Light extinction meters employing substantially identical measurment principles and producing substantially equivalent results but which employ other electronic and optical techniques may be used only after having been approved in advance by the Secretary.

(3) Recorder—a continuous recorder, with variable chart speed over a minimum range of 0.5 to 8.0 inches per minute (or equivalent) and an automatic marker indicating 1-second intervals shall be used for continuously recording the transient conditions of exhaust gas opacity, engine r.p.m. and torque. The recorder scale for opacity shall be linear and calibrated to read from 0 to 100 percent opacity full scale. The opacity trace shall have a resolution within 1 percent opacity. The recorder scale for engine r.p.m. and the recorder scale for observed engine torque shall be linear and shall have full scale calibration such as to facilitate chart reading. The r.p.m. trace shall have a resolution within 30 r.p.m. The torque trace shall have a resolution within 10 lb.-ft. Any means other than strip chart recorder may be used provided it produces a permanent visual data record of quality equal to or better than that described above.

(4) The recorder used with the smokemeter shall be capable of full-scale deflection in 0.5 second or less. The smokemeter-recorder combination may be damped so that signals with a frequency higher than 10 cycles per second are attenuated. A separate low-pass electronic filter with the following performance characteristics may be installed between the smokemeter and the recorder to achieve the high-frequency attenuation.

(i) 3 decibel point—10 cycles per second.

(ii) Insertion loss—zero ±0.5 decibels.

(iii) Selectivity—12 decibels per octave above 10 cycles per second.

(iv) Attenuation—27 decibles down at 40 cycles per second minimum.

(c) *Assembling equipment.* (1) The optical unit of the smokemeter shall be mounted radially to the exhaust pipe so that the measurement will be made at right angles to the axis of the exhaust plume. The distance from the optical centerline to the exhaust pipe outlet shall be 1.0 to 1.5 pipe diameters but never less

than 4 inches. The full flow of the exhaust stream shall be centered between the source and detector apertures (or windows and lenses) and on the axis of the light beam.

(2) Power shall be supplied to the control unit of the smokemeter in time at least 15 minutes prior to testing to allow for stabilization.

§ 85.125 Information to be recorded.

The following information shall be recorded with respect to each test:

(a) Test number.

(b) Date and time of day.

(c) Instrument operator.

(d) Engine operator.

(e) Engine identification numbers—Date of manufacture—Number of hours of operation accumulated on engine—Engine Family—Exhaust pipe diameter—Fuel injector type—Manufacturer measured fuel rate at maximum measured torque and horsepower—Air aspiration system—Low idle r p m—Maximum governed r p m—Maximum measured horsepower at r p m—Maximum measured torque at r p m—Exhaust system back pressure—Air inlet restriction.

(f) Smokemeter. Number—Zero control setting—Calibration control setting—Gain.

(g) Recorder chart. Identify zero traces—Calibration traces—Idle traces—Acceleration and lug-down test traces—Start and finish of each test.

(h) Ambient temperature in dynamometer testing room.

(i) Engine intake air temperature and humidity.

(j) Barometric pressure.

(k) Observed engine torque.

§ 85.126 Instrument checks.

(a) The smokemeter shall be checked according to the following procedure prior to each test:

(1) The optical surfaces of the optical section shall be checked to verify that they are clean and free of foreign material and fingerprints.

(2) The zero control shall be adjusted under conditions of "no smoke" to give a recorder trace of zero.

(3) Calibrated neutral density filters having approximately 20 percent and 40 percent opacity shall be employed to check the linearity of the instrument. The filter(s) shall be inserted in the light path perpendicular to the axis of the beam and adjacent to the opening from which the beam of light from the light source emanates, and the recorder response shall be noted. The nominal opacity value of the filter will be confirmed by the Secretary. Deviations in excess of 1 percent of the nominal opacity shall be corrected.

(b) The instruments for measuring and recording engine r p m, engine torque, air inlet restrictions, exhaust system back pressure, etc., which are used in the tests prescribed herein shall be calibrated from time to time in accordance with good technical practice.

§ 85.127 Test run.

(a) The temperature of the air supplied to the engine shall be between 68° F. and 86° F. The observed barometric pressure shall be between 28.5 inches and 31 inches Hg. Higher air temperature or lower barometric pressure may be used, if desired, but no allowance will be made for possible increased smoke emissions because of such conditions.

(b) The governor and fuel system shall have been adjusted to provide engine performance at the levels specified by the engine manufacturer for maximum rated horsepower and maximum rated torque. These specifications shall be reported in accordance with § 85.61 (b)(3).

(c) The following steps shall be taken for each test:

(1) Start cooling system.

(2) Starting with a warmed engine, determine by experimentation the dynamometer inertia and dynamometer load required to perform the acceleration in the dynamometer cycle for smoke emission tests (§ 85.128(a)(2)). In a manner appropriate for the dynamometer and controls being used, arrange to conduct the acceleration mode.

(3) Install smokemeter optical unit and connect it to the recorder. Connect the engine r p m and torque sensing devices to the recorder.

(4) Turn on purge air to the optical unit of the smokemeter, if purge air is used.

(5) Check and record zero and span settings of the smokemeter recorder at a chart speed of approximately 1 inch per minute. (The optical unit shall be retracted from its position about the exhaust stream if the engine is left running.)

(6) Precondition the engine by operating it for 10 minutes at maximum rated horsepower.

(7) Proceed with the sequence of smoke emission measurements on the engine dynamometer as prescribed in § 85.128.

(8) During the test sequence of § 85.128, continuously record smoke measurements, engine r p m, and torque at a chart speed of approximately 1 inch per minute minimum during the idle mode and transitional modes and 6 inches per minute minimum during the acceleration and lugging modes.

(9) Turn off engine.

(d) Check zero and recal if necessary and check span of the smokemeter recorder by inserting neutral density filters. If either zero or span drift is in excess of 5 percent opacity, the test results shall be invalidated.

§ 85.128 Chart reading.

(a) The following procedure shall be employed in reading the smokemeter recorder chart:

(1) Locate the acceleration mode (§ 85.128(a)(3)) and the lugging mode (§ 85.128(a)(4)) on the chart. Divide each mode into ½ second intervals beginning at the start of each mode. Determine the average smoke reading during each ½-second interval except those recorded during the transitional portions of the acceleration mode (§ 85.128(a)(3)(ii)) and the lugging mode (§ 85.128(a)(4)(ii)).

(2) Locate and record the 15 highest ½-second readings during the acceleration mode of each dynamometer cycle.

(3) Locate and record the five highest ½-second readings during the lugging mode of each dynamometer cycle.

§ 85.129 Calculations.

(a) Average the 40 readings in § 85.128 (a)(2) and designate the value as "a".

(b) Average the 15 readings in § 85.128 (a)(3) and designate the value as "b".

§ 85.130 Test engines.

(a) The engines covered by the application for certification will be divided into engine families based upon the criteria outlined in § 85.89(a).

(b) Emission data engines.

(1) Engines will be chosen to be run for emission data based upon engine family groupings. Within each engine family, the requirements of this paragraph must be met.

(2) Engines of each engine family will be divided into groups based upon exhaust emission control system. Two engines of each engine-system combination shall be run for smoke emission data as prescribed in § 85.123(b). Within each combination, the engines that feature the highest fuel feed per stroke, primarily at the speed of maximum rated torque and secondarily at rated speed, will be selected. In the case where more than one engine in an engine-system combination have the highest fuel feed per stroke, the engine with the highest maximum rated torque will be selected.

(c) Durability data engines.

(1) One engine from each engine-system combination shall be tested for lifetime smoke emission data as prescribed in § 85.123(c). Within each combination, the engine which features the highest fuel feed per stroke, primarily at rated speed and secondarily at the speed of maximum rated torque, will be selected for durability testing. In the case where more than one engine in an engine-system combination has the highest fuel feed per stroke, the engine with the highest maximum rated horsepower will be selected for durability testing.

(2) A manufacturer may elect to operate and test additional engines to represent any engine-system combination. The additional engines must be of the same model and fuel system as the engine selected in accordance with the provisions of subparagraph (1) of this paragraph. Notice of an intent to test additional engines shall be given to the Secretary not later than 30 days following the notification of the test fleet selection.

(d) Any manufacturer whose projected sales of new motor vehicle engines subject to this subpart for the model year

for which certification is sought is less than 300 engines may request a reduction in the number of test engines determined in accordance with the foregoing provisions of this section. The Secretary may agree to such lesser number as he determines would meet the objectives of this procedure.

(c) In lieu of testing an emission data or durability data vehicles elected under paragraph (b) or (c) of this section and submitting data therefor, a manufacturer may, with the prior written approval of the Secretary, submit data on a similar vehicle for which certification has previously been obtained.

§ 85.131 Maintenance.

(a) (1) Maintenance on the engines and fuel systems of durability engines may be performed only under the following provisions:

(i) One major engine servicing to manufacturer's specifications may be performed at 500 hours (±8 hours) of dynamometer operation. A major engine servicing shall be restricted to the following:

(a) Adjust low idle speed.
(b) Adjust valve lash if required.
(c) Adjust injector timing.
(d) Adjust governor.
(e) Clean and service injector tips.

(ii) Injectors may be changed if a persistent misfire is detected.

(iii) Normal engine lubrication service (engine oil change and oil filter, fuel filter, and air filter servicing and adjustment of drive belt tension, and engine bolt torque as required) will be allowed at manufacturer's recommended intervals.

(iv) Readjustment of the engine fuel rates may be performed only if there is a problem of dropping below 95 percent of maximum rated horsepower at 95-100 percent rated speed.

(v) Leaks in the fuel system, engine lubrication system and cooling system may be repaired.

(vi) Any other engine or fuel system maintenance or repairs will be allowed only with the advanced approval of the Secretary.

(2) Allowable maintenance on emission data engines shall be limited to the adjustment of engine low idle speed at the 125-hour test point.

(3) Complete emission tests (see §§ 85.131-85.138) shall be run before and after any engine maintenance which may reasonably be expected to affect emissions. These test data shall be supplied to the Secretary immediately after the tests along with a complete record of all pertinent maintenance, including an explanatory report of any malfunction encountered and the corrective action taken. In addition, all test data and maintenance reports shall be compiled and provided to the Secretary in accordance with § 85.84.

(4) If the Secretary determines that maintenance or repairs performed have resulted in a substantial change to the engine-system combination, the engine shall not be used as a durability data engine.

§ 85.132 Service accumulation and emission measurements.

Service accumulation shall be accomplished by operation of an engine on a dynamometer.

(a) Emission data engines: Each engine shall be operated on a dynamometer for 125 hours with the dynamometer and engine adjusted so that the engine is operating at 95-100 percent of rated speed and at least 95 percent of maximum rated horsepower. During such operation, the engine shall be run at the exhaust back pressure specified in § 85.135(c) and the air inlet restriction specified in § 85.135(d) except that the tolerances shall be ±0.5 inches of Hg. and ±2 inches of water respectively. Exhaust smoke tests shall be conducted at zero and 125 hours of operation.

(b) Durability data engines: Each engine shall be operated on a dynamometer for 1,000 hours with the dynamometer and engine adjusted so that the engine is operating at 95-100 percent of rated speed and at least 95 percent of maximum rated horsepower. During such operation, the engine shall be run at the exhaust back pressure specified in § 85.135(c) and the air inlet restriction specified in § 85.135(d) except that the tolerances shall be ±0.5 inches of Hg. and ±2 inches of water respectively. Exhaust smoke measurements shall be made at zero hours and at each 125 hours of operation. All results except the zero hour results shall be used to establish the deterioration factors (see § 85.133).

(c) All tests required by this subpart to be conducted after 125 hours of dynamometer operation or at any multiple of 125 hours may be conducted at any accumulated hours within 8 hours of 125 hours or the appropriate multiple of 125 hours, respectively.

(d) The results of each emission test shall be supplied to the Secretary immediately after the test. In addition, all test data shall be compiled and provided to the Secretary in accordance with § 85.84.

(e) Whenever the manufacturer proposes to operate and test an engine which may be used for emission or durability data, he shall provide the zero hour test data to the Secretary and make the engine available for such testing under § 85.84 as the Secretary may require before beginning to accumulate hours on the engine. Failure to comply with this requirement shall invalidate all test data submitted for this engine.

(f) Once a manufacturer begins to operate an emission data or durability data engine, as indicated by compliance with paragraph (e) of this section, he shall continue to run the engine to 125 hours or 1,000 hours, respectively, and the data from the engine shall be used in the calculations under § 85.133. Discontinuation of an engine shall be allowed only with the prior written consent of the Secretary.

§ 85.133 Compliance with emission standards.

(a) The emission standards in the regulations in this part apply to the lifetime emission of engines in public use. Prior to certification, lifetime emissions can be obtained by projection of test data to lifetime normal service. Lifetime normal service or its equivalent is taken to be 3,000 hours of prescribed dynamometer operation.

(b) It is expected that the opacity of exhaust emissions will change with use of the engine. It is assumed that the emission level corresponding to 1,000 hours of prescribed dynamometer operation is the average emission of an engine over its lifetime.

(c) The procedure for determining compliance with exhaust smoke emission standards for heavy duty diesel engines is as follows:

(1) Emission deterioration factors for the acceleration mode (designated as "A") and the lugging mode (designated as "B") shall be established separately for each engine-system combination.

(i) The applicable results to be used in determining the deterioration factors for each combination shall be:

(a) All emission data from the tests required under § 85.135(b), except the zero hour tests. This shall include the official test results, as determined in § 85.84, for all tests conducted on all durability engines of the combination selected under § 85.130(c) (including all engines elected to be operated by the manufacturer under § 85.130(c)(2)).

(b) All emission data from the tests conducted before and after the maintenance provided in § 85.131(a)(1)(i).

(ii) All applicable results shall be plotted as a function of the hours on the system, rounded to the nearest hour, and the best fit straight lines, fitted by the method of least squares, shall be drawn through these data points. The interpolated 125 and 1,000 hour points on this line must be within the standard provided in § 85.41 or the data shall not be used in calculation of a deterioration factor.

(iii) The deterioration factors will be calculated as follows:

A=percent opacity "a", interpolated to 1,000 hours, minus percent opacity "a," interpolated to 125 hours.

B=percent opacity "b", interpolated to 1,000 hours, minus percent opacity "b", interpolated to 125 hours.

(2) The "percent opacity" values to compare with the standards shall be the opacity values "a" and "b" for each emission data engine within an engine-system combination to which are added the respective factors "A" and "B" of subparagraph (1) of this paragraph for that engine-system combination: *Provided*, That if a deterioration factor as computed in subparagraph (1) of this paragraph is less than zero, that deterioration factor shall be zero for the purposes of this subparagraph.

(3) Every test engine of an engine family must comply with all applicable standards, as determined in subparagraph (2) of this paragraph, before any engine in that family will be certified.

APPENDIX B

CALIFORNIA EXHAUST EMISSIONS STANDARDS, TEST AND APPROVAL PROCEDURES FOR DIESEL ENGINES IN 1973 AND SUBSEQUENT MODEL YEAR VEHICLES OVER 6,001 POUNDS GROSS VEHICLE WEIGHT (CHASSIS DYNAMOMETER PROCEDURE)

D. Field Surveillance Chassis Dynamometer Test Procedure

I. Introduction

a) The following procedure may be used in the field surveillance testing of diesel-powered, heavy-duty vehicles.

b) The test procedure consists of a prescribed sequence of engine operating conditions using a vehicle chassis dynamometer with measurement of hydrocarbons, nitric oxide, and carbon monoxide during the same thirteen modes as used in the engine dynamometer procedure except the operating time in each mode is shortened to minimize tire failure problems.

c) This test procedure is similar to the engine dynamometer procedure except that the engine exhaust flow and brake horsepower are obtained from the engine manufacturers' data and fuel rate measurements during the test. Because of this and the greater difficulty in controlling test conditions, this procedure is inherently less accurate than the engine dynamometer procedure.

II. Fuel Specification

a) The fuel used for this procedure shall meet the same specifications required for the engine dynamometer procedure (Section C, II).

III. Instrumentation

a) Instrumentation shall be provided to measure the following:

1. Engine speed: rpm
2. Observed barometer: in. Hg
3. Water vapor pressure: in. Hg
4. Intake air restriction: in. water
5. Exhaust back pressure: in. Hg
6. Intake air temperature: ^{o}F
7. Fuel temperature at pump inlet: ^{o}F

b) Instrumentation shall be provided to measure the concentration of carbon monoxide, nitric oxide, and hydrocarbons in the exhaust as follows:

1. The determination of the carbon monoxide and nitric oxide concentrations shall be accomplished using sampling and analysis by nondispersive infrared methods using the SAE Recommended Practice #J177 titled "Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust" except the time in mode shall be as prescribed in Section D.V.a).

2. The determination of the hydrocarbon concentration shall be accomplished using sampling and analysis by a heated flame ionization detector method using the SAE Recommended Practice #J215 titled "Continuous Hydrocarbon Analysis of Diesel Exhaust" except the time in mode shall be as prescribed in Section D.V.a), 4).

c) Equipment shall be provided to measure the mass fuel consumption rate and to control the temperature of the fuel supplied to the engine. The fuel rate instrumentation must provide a continuous indication of fuel rate (weigh tank systems are not satisfactory). A system incorporating calibrated rotometers (fuel viscosity and temperature effect calibration) or a mass flow meter, a heat exchanger, and float tank similar to that shown in Figure 1 is satisfactory.

IV. Test Conditions

a) The following ranges of test conditions should be maintained as closely as possible during exhaust emission testing; deviations from these conditions will cause increasing errors in brake specific emissions values.

1. Intake air temperature: $85^0 \pm 15^0$ F

2. Barometric pressure: 29.4 in. Hg $\pm$ 1 in. Hg

3. Fuel temperature: 100^0 F $\pm$ 10^0 F

4. Intake restriction: between the manufacturers' published maximum limits of clean air cleaner restriction and dirty air cleaner restriction.

5. Exhaust restriction: typical encountered in the vehicle but no higher than manufacturers' published limit.

V. Test Procedure for Exhaust Emissions

a) Pre-Test Conditioning

Operate the vehicle on the chassis dynamometer with the engine at 85 $\pm$ 10% of rated speed and 50 $\pm$ 10% of maximum rear wheel horsepower at that speed for at least 15 minutes or until the transmission and rear axle temperatures have stabilized.

b) Selection of Test Conditions

1. Determine the maximum fuel rate for the test engine at the rated and intermediate engine speeds.

2. Obtain curves of engine brake horsepower and exhaust flow as functions of fuel rate for the engine model being tested from the engine manufacturer (Figures 2 and 3).

3. Use the brake horsepower vs. fuel rate data (Fig. 2) to estimate the maximum brake horsepower produced by the test engine at the rated and intermediate speeds. These are the 100% load conditions to be used during the test.

4. Calculate the engine brake horsepower at 75, 50, and 25% load for rated and intermediate speeds using the estimated maximum brake horsepower values from D,V(b) (3) above.

FIGURE 1

FUEL FLOW MEASUREMENT SYSTEM

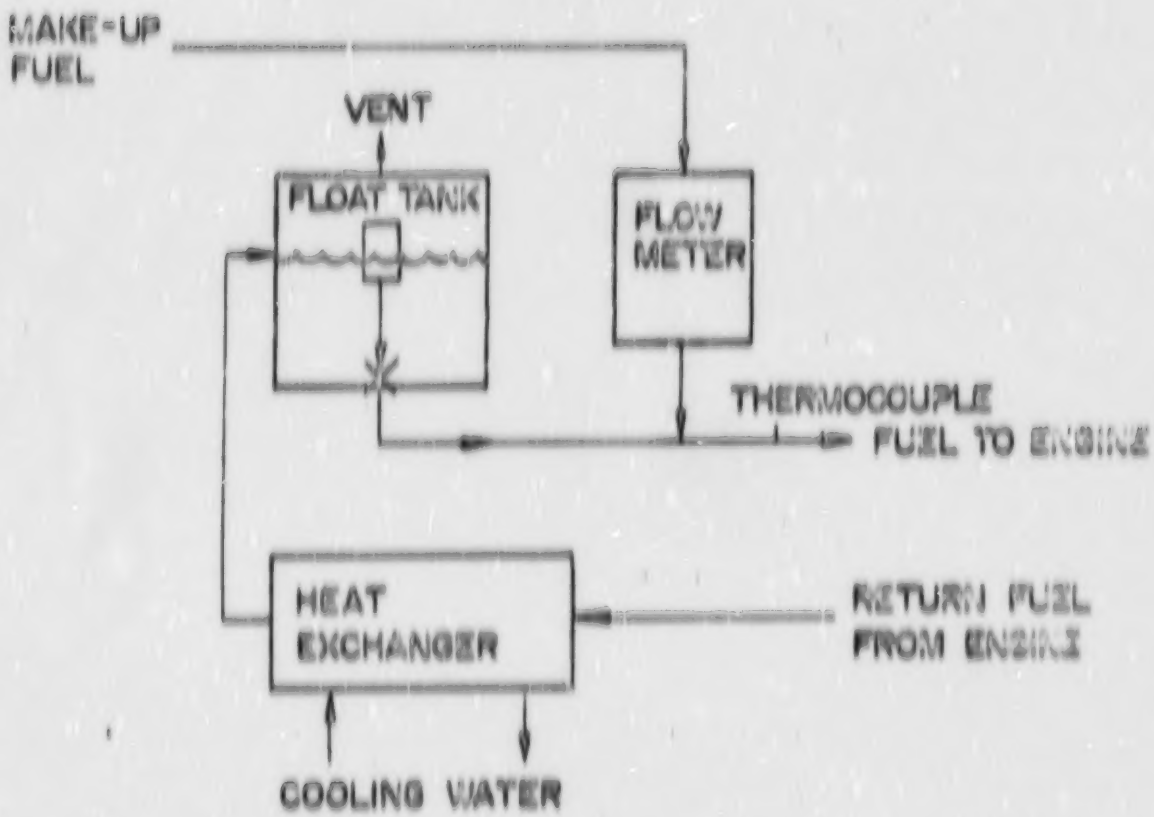
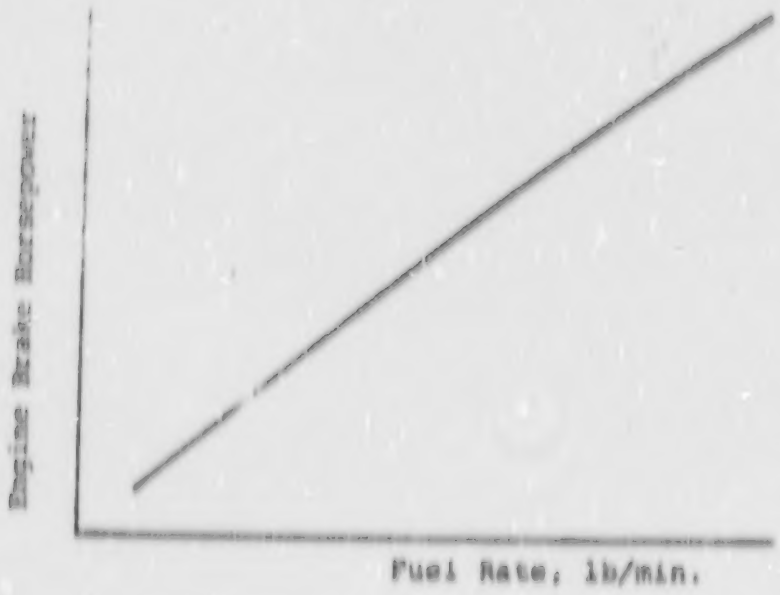


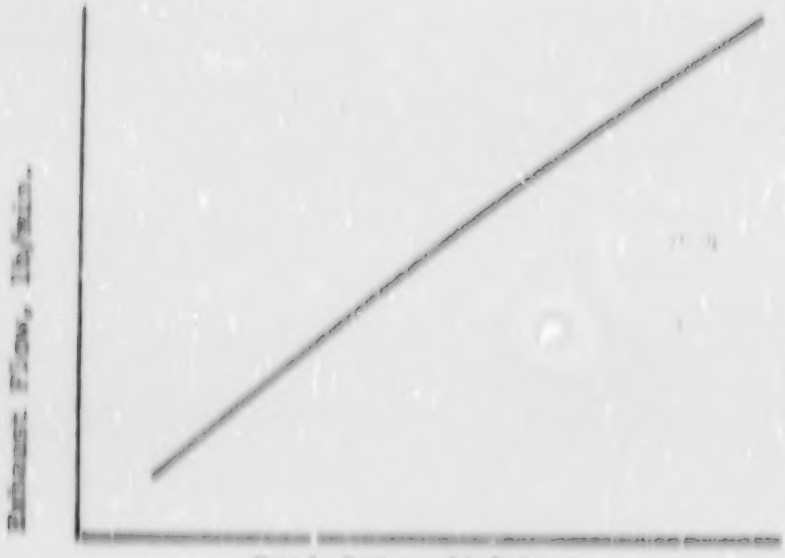
Figure 2



Engine Model AAAA

Engine Speed XXXX

Figure 3



Engine Model AAAA

Engine Speed XXXX

5. Determine the fuel rates associated with the engine brake horsepower values calculated in D, V(b) (4) above from Fig. 5.

6. Operate the vehicle and determine the rear wheel horsepower values associated with speed/fuel rate condition.

c) Emissions Test Procedure

1. Warm up engine, transmission and rear axle by operating at rated engine speed and 30-50 mph for at least 15 minutes or until engine oil and transmission temperatures have stabilized.

2. Record the barometer and vapor pressure at the beginning of the test.

3. Operate the engine at the following modes using fuel rate values within ± 5% of the calculated in Section D,V,(b). Use the rear wheel horsepower values observed in Section D,V,(b) (6) to adjust the accelerator and dynamometer settin s to reach proper test conditions.

Engine Speed	Percent Load
Low Idle	Declutched
Intermediate	Declutched
Intermediate	25%
Intermediate	50%
Intermediate	75%
Intermediate	100%
Low Idle	Declutched
Rated	100%
Rated	75%
Rated	50%
Rated	25%
Rated	Declutched
Low Idle	Declutched

4. Operate the engine for three minutes in each mode allowing up to one minute for engine speed or load changes, at least one minute for emission stabilization, and one minute for emission measurement.

i) Record the following during the complete test. Exhaust sample shall be flowing through the analyzers during the entire test.

a) Hydrocarbon analyzer output
b) Carbon monoxide analyzer output
c) Nitric oxide analyzer output

ii) Record the following data during the final minute in each mode:

a) Engine Speed
b) Fuel flow rate
c) Fuel temperature at pump inlet
d) Intake air temperature
e) Intake air restriction
f) Exhaust restriction

d) Chart Reading

1. Locate the last sixty seconds of each mode and determine the average chart reading for hydrocarbons, carbon monoxide, and nitric oxide over this one minute period. (This chart reading procedure shall be followed rather than the times specified in the SAE Recommended Practices referenced in Section D,III(b)).

2. Determine the concentration of HC, CO, and NO (HC_{conc}; CO_{conc}; NO_{conc}) in each mode from the chart reading D,V(d) (1) and from the calibration data. Average the three idle modes.

3. Determine the engine brake horsepower and mass exhaust flow from the manufacturer's data using the fuel rate measured during each mode from Figures 2 and 3.

e) Calculations

1. The test results for the emissions test sequences shall be derived through the following steps:

i) Calculate the mass emissions for HC, CO, and NO in grams per hour for each mode as follows:

$HC_{mass} = 0.0132 \times HC_{conc}$ (ppm-carbon) x exh mass (lb/min)

$CO_{mass} = 0.0263 \times CO_{conc}$ (ppm) x exh mass (lb/min)

$NO_{2mass} = 0.0432 \times NO_{conc}$ (ppm) x exh mass (lb/min)

ii) Calculate the weighted BHP, HC_{mass}; CO_{mass}; and NO_{2mass} for each mode by multiplying the value of each by the weighting factor for that mode. The weighting factors are 0.20 for the average idle mode and 0.06 for all other modes.

iii) Calculate the brake specific emissions for HC, CO, and NO as follows:

$$BSHC = \frac{\Sigma (HC_{mass} \times WF)}{\Sigma (BHP \times WF)}$$

$$BSCO = \frac{\Sigma (CO_{mass} \times WF)}{\Sigma (BHP \times WF)}$$

$$BSNO_2 = \frac{\Sigma (NO_{2mass} \times WF)}{\Sigma (BHP \times WF)}$$